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AN OPTICAL ANALYSIS OF THE FARRAND VCASS HELMET-MOUNTED DISPLAY

R. A. BUCHROEDER

OPTICAL DESIGN SERVICE
TUCSON, ARIZONA 85716

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AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
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Optical design and component testing have been examined for a new wide-angle, helmet-mounted dual-eye display designed by the Farrand Optical Company, Inc., Valhalla, New York, as part of the Visually Coupled Airborne Systems Simulator (VCASS) program. The display uses a Farrand-proprietary technical device called the Pancake Window™, and two 19-mm miniature cathode ray tubes that are mounted with their optics on a modified pilot's helmet. The device weighs 2.3 kg (5.1 lb). Separately adjustable monocular displays provide overlapping

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20. Abstract--continued

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images for a panoramic display up to 140° wide by 60° tall. Each eye has its own 15-mm exit pupil and enough eye relief to allow ordinary eyeglasses to be worn. The display is permanently set at zero diopter focus to eliminate parallex. Interpupillary distance is adjustable, while accommodation for different head sizes is provided by altering the helmet liner with simple spacers. Optical quality would allow resolution of 2000 TV lines, and vignetting is nonexistent over most of the field of view. Although the optical design is difficult by conventional standards, optical tests made on the device prove the manufacturability of the optics.

SUMMARY

This report provides an indepth analysis and explanation of the Visually Coupled Airborne Systems Simulator (VCASS) helmet-mounted display (HMD) designed by the Farrand Optical Company, Inc., under Air Force Contract F33615-78-C-0512. The optical properties of the VCASS display are independently verified by the author and elaborated upon in more detail than that provided in Farrand documentation. In particular, much greater detail is provided concerning the Pancake Window™ theory of operation, final design tradeoffs, acceptance test analysis, and the feasibility of design enhancements. The report concludes that further evolution and refinement of the VCASS HMD is possible and establishes the general tradeoffs that must be made between image quality, field-of-view, exit pupil, and the overall size of the optical system.

PREFACE

This report was prepared under the direction and sponsorship of the Aerospace Medical Research Laboratory, Human Engineering Division, Visual Display Systems Branch of the United States Air Force as part of Project 71842601. Mr. Dean F. Kocian was the program technical monitor. The impetus for this study arose from developmental work and testing performed with this unique two-eye display as part of the VCASS system. The goal of this work was to insure that underlying technical principles were clearly understood and to promote an efficient design development process if display design changes were implemented as a result of VCASS testing.

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1. INTRODUCTION

This report provides an overview of the optical system performance of the Visually Coupled Airborne Systems Simulator (VCASS) helmet-mounted display (HMD) designed by the Farrand Optical Company, Inc., under Air Force Contract F33615-78-C-0512. The optical properties of VCASS have been independently verified by the author[1] for this report, and some points that were beyond the scope of Farrand's work have been examined and explained.

The Farrand VCASS HMD is based on the principle of overlapping the fields of view of two wide-angle monocular magnifiers.[2] Farrand has also developed a wide-angle display with the trade name "Pancake Window™," on which they hold at least one patent (USP 3,940,203). VCASS is the first application of the Pancake Window™ to a miniature eyepiece version.

Further evolution and refinement of the VCASS HMD, which utilizes two 80° field of view monoculars and a large, 15-mm exit pupil, is possible, but first experience must be gained with the Farrand prototypes to improve our understanding of this complex display.

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1. R. A. Buchroeder et al., "Design of a Catadioptric VCASS Helmet-Mounted Display," AFAMRL-TR-81-133, Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, November 1981.
2. M. Shenker, J. LaRussa, R. R. Yoder, Jr., and W. H. Scidmore, "Overlapping Monoculars--An Ultrawide-Field Viewing System," Appl. Opt. 1, 399 (1962).

2. DESIGN CONSIDERATIONS

2.1. Helmet

The visor and related fixtures of the HGU-22/P extra large helmet were removed, and fixtures to connect the display were added (see drawings in Appendix). Farrand measured the weight of the modified helmet, without display, at 0.7 kg (24.5 oz), with center of gravity located at $\overline{X}$ = +1.16 cm (0.46 in.) and $\overline{Y}$ = +1.72 cm (0.68 in.) relative to the helmet centerline shown on AFSC ASD Drawing No. 65D1581, Rev. G.

2.2. Limitations on Size of Display

VCASS is intended to serve as an engineering research tool to explore the utility and applications of visually coupled systems technology.

The VCASS HMD will be worn by an observer seated in a cockpit. It may later be modified to be used in an actual aircraft cockpit with the canopy down. Thus vertical protrusions from the display, such as the "rabbit ears" of top-mounted CRTs cannot be included and weight/size should be kept to a minimum.

Weight and moment of inertia should be minimized to allow free movement of the head.

2.3. Head Position Sensing

Currently, a magnetic helmet sensing transducer is used to sense helmet position and orientation. The use of metallic materials in the display must be kept to a minimum to avoid interference with the magnetic transducer system.

2.4. Image Generator

2.4.1. Miniature CRTs on Helmet

A CRT of high resolution, at least 1000 TV lines, is required because of the high magnification needed to produce a wide-angle display. Image brightness depends only on the luminance of the CRT and the transmission of the optical system, provided the exit pupil completely fills the eye.

The prototype display uses a Thomas Electronics, Inc. miniature CRT. Its image area is approximately 19 mm in diameter, truncated top and bottom for a vertical dimension of about 15 mm. The present design uses a nearly monochromatic P53 green phosphor. The tube has a fiberoptic faceplate that has a concave radius of 150 mm to permit optimum focus with the optical system.

2.4.2. CRTs Off the Helmet with FFOB

The high-voltage leads to the helmet-mounted CRTs pose a potential safety consideration that is eliminated by using CRTs coupled to the helmet with flexible fiberoptic bundles (FFOB). Additionally, a FFOB can be arranged to optimize weight distribution on the helmet, while minimizing the size of the display.

Luminance is the property of an illuminated surface or self-luminous source that is perceived as brightness, measured in foot-Lamberts. Larger CRTs can be driven with higher beam currents without losing the requisite number of TV lines, thereby allowing luminance to be increased severalfold. However, the CRT image must be transferred through the fiberoptics to the HMD optics which leads to losses in resolution and luminance.

The fiber optic image fibers are covered with a lower refractive index material, called cladding, to prevent light transference, or crosstalk,

between fibers. The phenomenon of total internal reflection is required to achieve high transmission; no metallic coating would suffice. Curiously enough, there is an electromagnetic field surrounding the fiber, called an evanescent wave that dies out fairly quickly. The cladding itself must be nonabsorbing, and sufficiently thick to prevent this wave fron interacting with adjacent fibers. A cladding thickness of about 2 waves, or 1 μm, is preferred. It is apparent that if the fibers are 10 μm in diameter, a clad diameter of 12 μm is required. The area comprising the cladding is 30%, and if the fibers are packed as closely as possible, the unfilled areas (interstices) between clad fibers cause another 10% loss in image area. Therefore, a 10-μm fiber bundle will in general never be more efficient than 60%. If bundles of different sizes are coupled together, then the transmission can be obtained as the product of their separate transmissions. Therefore, if two bundles are cemented together, a net transmission of around 36% can be estimated. Consequently, a beam of light needs to be approximately 3 times stronger to equal a beam not transferred through such fiberoptics.

The matter of resolution is equally disturbing. To separate two points, the points must be apart by more than two fiber diameters. If 10-μm fibers are coupled to a 19-mm faceplate, it is possible to resolve no more than approximately 900 line pairs, at virtually zero MTF. When bundles of different fiber sizes are joined, the resolution drops empirically by an inverse square sum rule. Thus, if two bundles of the same fiber diameter are joined, the resolution drops by 30%, but when a fine bundle is joined to a significantly coarser bundle, the result is almost the same as that given by the coarser bundle.

A candidate optical conduit has the following dimensions. Its length, which is flexible, is 1.8 m. The bundle comprises 10-μm fibers organized into rectangular or hexagonal matrices of 25 or 36 fibers to fill a circular format 19 mm in diameter. The end connecting to the display is fixed in epoxy and ground and polished to the shape required by the optical design. The other end is likewise fixed in epoxy and either bonded or placed in close contact with the fiberoptic faceplate of a 2.54-cm miniature CRT, with 3-μm fibers. As explained in the previous paragraph, the net transmission of such a configuration would be lower than that from a CRT directly connected to the display. However, the 3-μm faceplate exists in either event, so the reduction in transmission compared with a helmet-mounted CRT is only approximately 40%. The resolution, however, is now limited by the 10-μm fiber to about 900 line pairs.

The weight of a 1.8-m bundle would be about 1.3 kg.

2.4.3. Light Valve and FFOB

Probably the brightest projected television image that can be achieved at the present time is with the General Electric "light valve." The General Electric Company has supplied us with information about the principle of their version, which is used extensively for large screen projection.

The GE projectors weigh approximately 68 kg and typically require from 1000 to 1600 W of power, most of which is used to drive a xenon arc. Prospective users should not forget that the heat from these projectors must be vented.

The manner in which the GE light valve works is illustrated in Figure 1. Illumination from a white-light xenon arc at the left passes through a

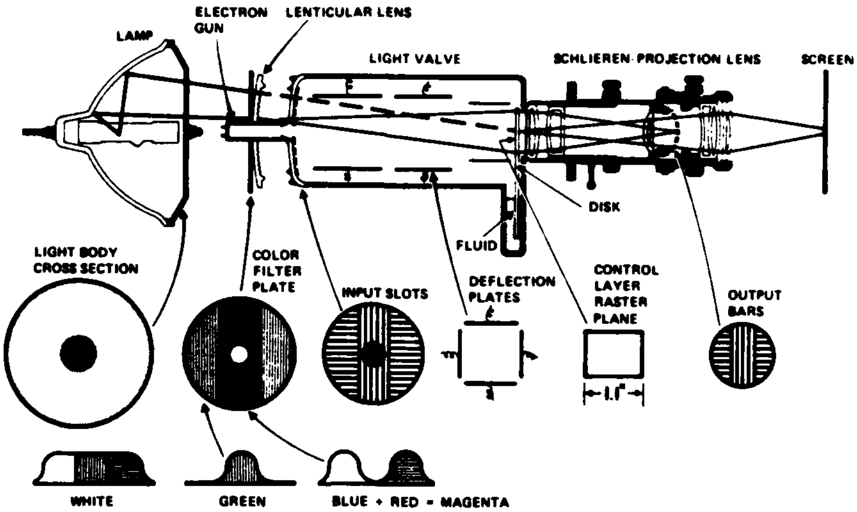


Figure 1. Operating principle of the General Electric light valve projector (courtesy of General Electric and Proc. SPIE).

color filter plate that has two green stripes and one magenta stripe. A lenticular plate enhances the transmission by directing the arc light to the input slot mask, which corresponds spatially to the initial color filter plate. This mask acts as the effective light source, much like the filaments in an ordinary projector. The mask is then reimaged by a set of lenses near the control layer raster plane to form a real exit pupil near a second set of lenses that project an image of the control layer raster plane. At the real exit pupil is placed a second output bar mask. The clear parts on this mask correspond to the blocked parts on the input mask and vice versa. Now, when the control layer, which is created by revolving a clear disk into a pool of high-viscosity transparent fluid, is undisturbed, all the light that passes through the input slot mask is completely blocked by the output bar mask. If we disturb the shape of the

control layer, light is diverted from its normal path and escapes through the output bar mask. The next step is to generate red, blue, and green images.

The chamber of the light valve is evacuated and held at a vacuum by a pump, which is needed since the fluid slowly volatilizes. A single electron beam is generated by the electron gun and is deflected by two sets of deflection plates. As in normal television, horizontal and vertical sweep voltages are applied to the deflection plates to produce a raster. The light valve modulates the horizontal sweep with two carrier frequencies, inversely proportional to the wavelength of the light being coded, one at 16 MHz for red, the other at 12 MHz for blue light.

The revolving disk, which is covered with an oil film, has a thin transparent conductive coating that attracts the electron beam, which then produces transient grooves similar to those in a diffraction grating. Note that when there is no modulation of the carrier frequency, no light diffracts from the zero or direct order. As the modulation increases, the grooves become deeper, and more light is diffracted into the various orders to the left and right of center. To obtain color images, all but the red and blue diffracted images are blocked off; this is accomplished with the output bar mask. The brightness of each color is therefore controlled by adjusting the carrier modulation.

The green image is produced differently. The vertical sweep is modulated at 48 MHz, which is unrelated to the wavelength of green. The pre-existing raster lines form a diffraction grating. These lines can be eliminated by moving them vertically until they spread out enough to touch each other, producing a uniform (green) field that will not diffract and

therefore not transmit through the output bar mask. Thus the green signal information is inversely proportional to the modulation of the 48-MHz carrier. Since all three images share a common axis of symmetry, there are no oblique color effects as occur with multiple-lens projectors. The colors here are spectral and thus capable of a richness not possible with CRT phosphors.

Obviously a light valve projector is too large and too hot to be mounted in a cockpit, so the image must be delivered through a FFOB. A problem arises with fiberoptics coupled to the light valve, evidently one serious enough that a solution is still being sought by Farrand with the assistance of the American Optical Company, which makes fiberoptics.

The exit pupil of the light valve consists of a bilaterally symmetric but not uniform pattern of vertical magenta bars and horizontal green bars. There is a sizable hole in the middle, which is due to the obstruction of the arc structure and electron gun.

As may be seen in Figure 2, a fiber preserves angular but not spatial information about a ray. A stripe of light will be transformed into a nonuniform ring of light. The light from the light valve will consequently be transformed from its striped pattern into a nonuniform ring pattern. The pattern produced in our exit pupil will be an image of this distribution, so it will be empty in the middle and green-rich toward its outer edge.

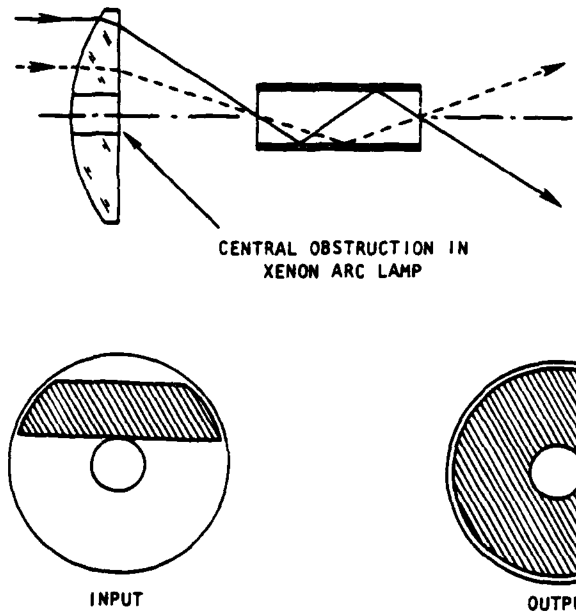


Figure 2. Fiberoptics conserve angular but not spatial distribution.

2.5. Optical Specifications

2.5.1. Field of View--Panorama Adjustment

The optical system for each eye is designed to have a field 80° wide by 60° tall, which is derived from a 19-mm diameter CRT image.

Conceptually, the optical axes of the two displays can be tilted outward by equal amounts from the forward line of sight to provide a wide-field panoramic image. The basic concept is illustrated in Figure 3. The amount of overlap is adjustable from 20° to 60° (axes tilted from 30° to 10°).

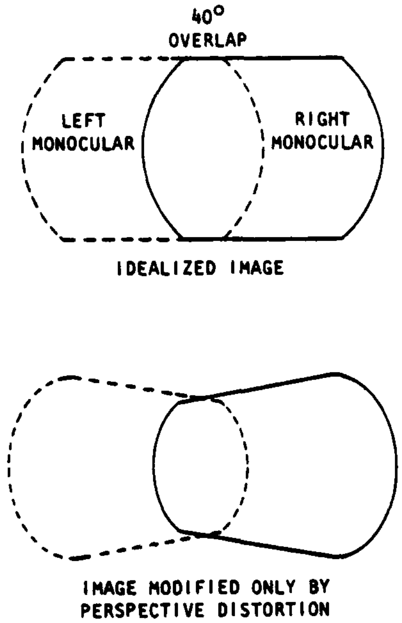


Figure 3. Panoramic display produced by overlapping monocular images.

2.5.2. Eye Relief

Nominal eye relief (axial separation to the nearest optical component measured from the exit pupil to the Pancake Window^{TM}) is 39.5 mm. Because the left eye display optics interfere with the right eye's optics, the smaller the eye relief, the greater can be the image overlap.

2.5.3. Exit Pupil Diameter

The nominal exit pupil diameter is 15 mm. Since there must be a hard aperture stop in the optical relay of the design, the actual shape and size will vary over the field of view because of pupil aberration.

2.5.4. Transmission

Original goals for transmission were waived to permit use of the Pancake Window™ principle. Typical final transmissions are 0.7% for the CRT path and 2.3% for the see-through path. Special coatings cannot greatly enhance these values.

2.5.5 IPD and Focus Adjustment

The interpupillary distance (IPD) is adjustable from 62 to 72 mm. The smaller the IPD, the more restricted is the possibility for overlapping the two fields of view. If large exit pupil diameters could be achieved, we could dispense with IPD adjustment.

Focus adjustment for different states of accommodation is not provided. It may be unwise to allow focus adjustment in binocular displays because only when the displays are set for zero diopter focus does the line of sight remain independent of centering the eyes in the exit pupil. In VCASS, defocus would manifest itself as a dynamic parallax error.

Nominal focusing is achieved by moving the miniature CRTs relative to the relay lens housing. The nominal focal length of the Farrand design is 13.67 mm, from which diopter calibration can be derived.

2.5.6. Collimation

The principal reason for overlapping the displays was originally to blend the two images together. Although stereoscopic vision would be possible, this was a secondary objective. The large field of image overlap would be more suited to stereoscopic display.

For the images to blend and for stereoperception to be possible, the two images must match to some precision. A requirement for 2% match in nominal magnification provides image similarity in shape. Divergence of 0

minutes and convergence of 8 minutes of arc have been set. The relative rotation of one image should be defined with respect to the other, and to the meridian, within typically 30 minutes of arc. Because apparent magnification in this kind of display is anamorphic, that is, not rotationally symmetric, finer details remain to be settled after experience with the prototypes.

2.5.7. MTF

The modulation transfer function (MTF) is a measure of image contrast at different spatial frequencies, and the performance of the optical design is prescribed in terms of MTF curves. These are shown, compared with the final design values, in Section 4.3.

2.5.8. Color Correction

The design must work well with a narrow spectrum phosphor such as the P53, and in addition, should be achromatic to permit use of the display with other image generators such as beam penetration phosphors and light valves. The chromatic MTF of the final design is only slightly inferior to the monochromatic MTF, and still exceeds the monochromatic MTF specification.

2.5.9. Distortion

Distortion is the combined eyes' perception of improper angular mapping of an object simulated to lie in the field of view. The intention is that the perceived mapping error will be less than 2%. Many wide-angle binoculars have distortion in excess of 10%.

3. DESIGN DEVELOPMENT

3.1. Refractive Helmet Mounted Displays

Refractive HMDs have the advantage of high transmission, and fields up to 40° have been achieved. However, limits on the field of view and the exit pupil are imposed optically by oblique aberrations as well as in a more subtle sense by chromatic aberration of the exit pupil. Additionally, from a practical standpoint the size, thickness, and consequent weight of certain glass elements become excessive. For the present application, see-through requirements seriously inhibit the maximum field that can be achieved with a refractive display.

3.2. Folded Catadioptric Displays

Some of the possibilities with this form of display for VCASS were extensively explored and reported in AFAMRL-TR-81-133, "Design of a Catadioptric VCASS Helmet-Mounted Display," where a design with a field of 70° and an exit pupil of 12 mm was achieved only with difficulty.

Catadioptric displays have an inherent advantage over refractive displays: one element acts both as a transmitter and a reflector, so the see-through field of view can be large. No thick lens elements, as would be needed for a refractive display, are involved in a catadioptric display.

3.3. Farrand Pancake Window™ Display

Farrand Optical Company, Inc., has made extensive use of the Pancake Window™ concept for magnifying large CRTs in aircraft simulators. The principle of operation is described in U.S. Patent 3,940,203 for a holographic version. The principle is the same for the catadioptric form used in VCASS and can be explained with Figure 4. Consider that there is a

light source, either a CRT phosphor or, as in the present case, the intermediate image formed by the relay optics. The goal is to form a magnified virtual image at infinity by using the concave mirror of the Pancake Window™ as an eyepiece. This is accomplished with partially reflective coatings as shown. However, at this point the unmagnified image is superimposed on the magnified image. This must be eliminated for the Pancake Window™ to be useful. To achieve this, the light from the source is polarized. Figure 4 shows the polarizer in front of an image source. In the Farrand design it is enclosed in the cell holding the relay optics.

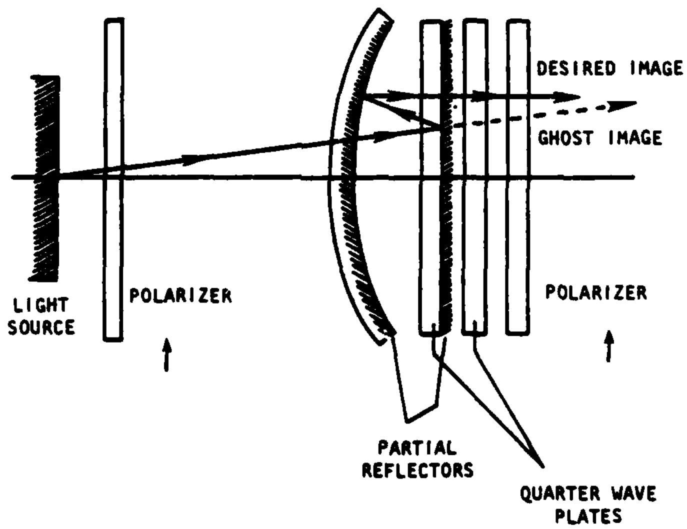


Figure 4. Principle of the Pancake Window™

The spherical reflector is ordinary except for its 50:50 coating. Next, a quarter-wave plate with a 50:50 coating on its second surface is placed in position. Now, half the light passes through the coating and must be eliminated before reaching the eye. This is done by using a second

quarter-wave plate, and finally a polarizer whose axis is aligned with that of the first polarizer. The reflected light, meanwhile, has passed back through the first quarter-wave plate, thus giving one-half wave retardation to the beam. It reflects off the concave reflector and is collimated, then goes back through the partially reflective quarter-wave plate, through the second quarter-wave plate, and up to the last polarizer.

How does this beam differ from the straight-through beam? The effect of one-half wave of retardation is to turn the plane of polarization of the input beam by 90°, so that its plane of polarization is at right angles to that of the output polarizer. This theoretically eliminates the unwanted beam. The doubly reflected beam, however, passes through a quarter-wave plate four times, so that it experiences a full wave of retardation. The first half-wave turned it 90°, the second one turned it another 90°, so it once again has its plane of polarization aligned with that of the output polarizer and is therefore visible to the eye. Unfortunately, the transmission of this system is inherently low, and there seems to be no way to avoid this problem.

3.4. Two Forms of the Pancake Window™ Display

The low transmission of the display led Farrand to explore an alternative form. As shown in the right-hand sketch of Figure 5, the need for a flat beam-combining plate causes a significant loss both in the CRT image path and in the see-through path. Farrand therefore explored a modification of the design that eliminates the beam combiner, as shown in the left-hand sketch. This form, which also leads to good imagery, was rejected because, as may be observed, it intrudes on the available eye relief.

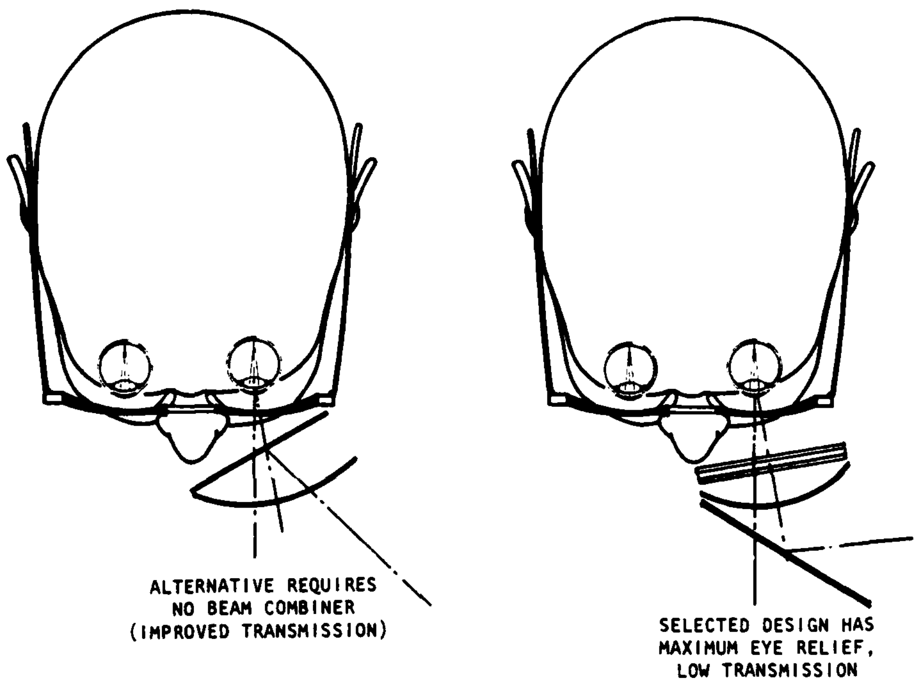


Figure 5. Two distinctive embodiments of the Pancake Window™ principle.

This second form is similar to that of conventional folded catadioptric displays; however, in wide angle embodiments the pancake's quarter-wave plates and polarizers are necessary to avoid unwanted nonfocussed images.

3.5. Some General Optical Design Tradeoffs

The imaging problem is involved in a very complicated way with mechanical problems associated with assembling two bulky wide-angle monoculars to form a binocular HMD. The optical designer has a variety of compromises to make, and the choices made by a team at the University of Arizona were different from those made by Farrand.

Arizona elected to design for a flat field with zero optical distortion. The use of conventional catadioptric folding concepts led to a maximum monocular field of only 70°. Simplicity of the optical design, whose relay contains just five lens elements, restricted the pupil to 12 mm.

Farrand, in using its Pancake Window™, was easily able to obtain an 80° field of view. With a complex intermediate image relay group comprising 11 elements, they also achieved a very high-quality 15-mm exit pupil, but on a curved field. As a further aid to mechanical design and optimum image quality, the Farrand design allowed up to 17% optical distortion. This distortion was not mandatory, but its correction would involve major optical changes in the existing design. Likewise, field curvature could be eliminated, but only by an optical redesign.

The advantage of eliminating optical distortion and field curvature is that these problems do not need to be compensated by the computer or CRT electronics. Centration of the CRT image then becomes usable as a means

for collimation that is comparatively insensitive to focus and image tilt errors.

Therefore, it is possible to envision a Pancake Window™ design with or without optical distortion, with or without a flat image field, and with a range of exit pupil diameters different from the present 15-mm value. This shall be discussed in greater detail, but first let us consider image overlap.

By making the optical axes of the two separate monoculars diverge, a wide-angle panoramic binocular was obtained, but at the same time only a limited area of overlapping images occurred in which redundancy or stereoscopic imagery was achieved. It is regarded as being desirable, at least as an option, to be able to sacrifice the wide field for an overlapping field. Basically, this depends on eyerelief and interpupillary distance (IPD) in an uncluttered Pancake Window™ design. The numbers can be refined to include fractional vignetting of the pupil, but ignoring that calculation for clarity, the total angular overlap of monocular fields can be approximated as:

$$\text{Overlapping Field} \approx 2 \times \text{arctangent } (1/2 \text{ IPD/Eyerelief}).$$

For a 62-mm IPD and a 40° semifield angle, this equation leads to an eyerelief of 37 mm. However, this value ignores the fact that vignetting would be 50% in the ideal case, that the Pancake elements have some thickness, and that allowance must be made for mounting them. Therefore, the eyerelief would be shorter. Since one eye must not see the other eye's image, schemes should be avoided that would allow overlapping images with leaks or ghosts.

To facilitate wearing the display, it is advantageous to have exit pupils much larger than the pupil of the eye. This allows the size of the helmet to be less critical and compensates for pupil shift caused by pivoting the eyes in their sockets.

Provided that the output numerical aperture of the relay does not exceed 1.0, it is not necessary to optically bond the relay to the image generator. It is assumed that the CRT size is unchanged, although increasing its diameter or increasing it optically with fiberoptic magnification or with a bonded magnifying lens is highly advantageous optically (but, unfortunately, not in terms of size and weight). Presently, the pupil is 15 mm in diameter with a numerical aperture (NA) of 0.55, so scaling yields NA = 0.74 at 20 mm and NA = 0.92 at a 25-mm exit pupil diameter. The 25-mm pupil would probably require bonded contact or a fiberoptic magnifier. The 20-mm pupil is probably realizable with a design modification.

The impact of this modification can be estimated. Although the use of aspheric surfaces is powerful, allowance should be made for some additional elements. To the level of third order aberration, spherical aberration will be the principal problem, and will increase at least as the third power of the increase in numerical aperture. However, dividing one element into two permits a reduction in the spherical aberration by a factor of eight. Therefore, the number of elements should probably increase at the same rate as the increase in speed to be safe. There should be allowance for three to four more elements in the relay section of the HMD. Alternatively the MTF specification can be reduced and more vigorous use made of the aspherics in the present design, or a different

configuration can be chosen.

The relay section will naturally increase in diameter at the same rate that the diameter of the pupil increases; the weight will rise more rapidly than the diameter.

If the field of view is reduced, a constant level of complexity is given approximately by the Lagrange invariant, Q = (pupil/2)(field angle/2). A 60° field with a 20-mm pupil and a 50° field with a 24-mm pupil are likely to be similar in size and shape to the present design, which is intended for an 80° field with a 15-mm pupil. A 60° field with a 25-mm pupil requires an increase in optical complexity.

If 60° to 50° designs are desired with only 15-mm pupils, then the number of elements will be reduced, and the overall weight and complexity of the HMD will be more favorable. Since the existing Farrand design is capable of a 60° overlap, any modification of it should be able to achieve that overlap too, provided the pupil is allowed to vignette as it does now.

If a P53 monochromatic phosphor were used, the lenses could be non-achromatic. This would ordinarily reduce the complexity of any selected lens configuration. In the Arizona form, the five-element relay becomes a three-element design of even superior quality.

The Farrand relay is of Petzval lens form, and under less stringent MTF requirements would comprise only spherical lens elements. The design requires a large number of elements for monochromatic correction, thus color correction does not add a great burden. The aspheric surfaces of the design could probably be obviated by adding a few additional elements, which would add to the weight problem.

It is difficult to make generalizations about configurations that involve complicated packaging considerations. Perfectly sensible optical design solutions may be found useless for a HMD, and it is often advantageous to bend the rules in one area in order to obtain a greater mechanical advantage in another. Both Farrand and the University of Arizona worked diligently along similar but separate paths and came to many similar conclusions, even though each was unaware of the details of what the other was doing. The problems for a wide angle display were, on the whole, given a great deal of attention in these two studies, and of the two, the Farrand design represents a closer approach to optical perfection.

3.6 Image Orientation through Pancake Window™ Display

Figure 6 shows corresponding images through the display. The Pancake Window™ is equivalent to a single-lens magnifier. It produces a virtual image at infinity, and this image has the same orientation as the image at its focal plane. The effect of rotating the prism about the optical axis is to cause this image to rotate. Therefore, for any orientation of the prism, there is a suitable rotation of the CRT that will give a perfectly aligned apparent image at infinity.

The figure shows fold angles at 90°; however, the same result applies at any set of angles, and derives from the fact that there are two reflections and one image rotation from the relay optics. Therefore, regardless of the contortions through which the optical path is folded, rotating the CRT is always sufficient to produce an image right-side up with the proper handedness.

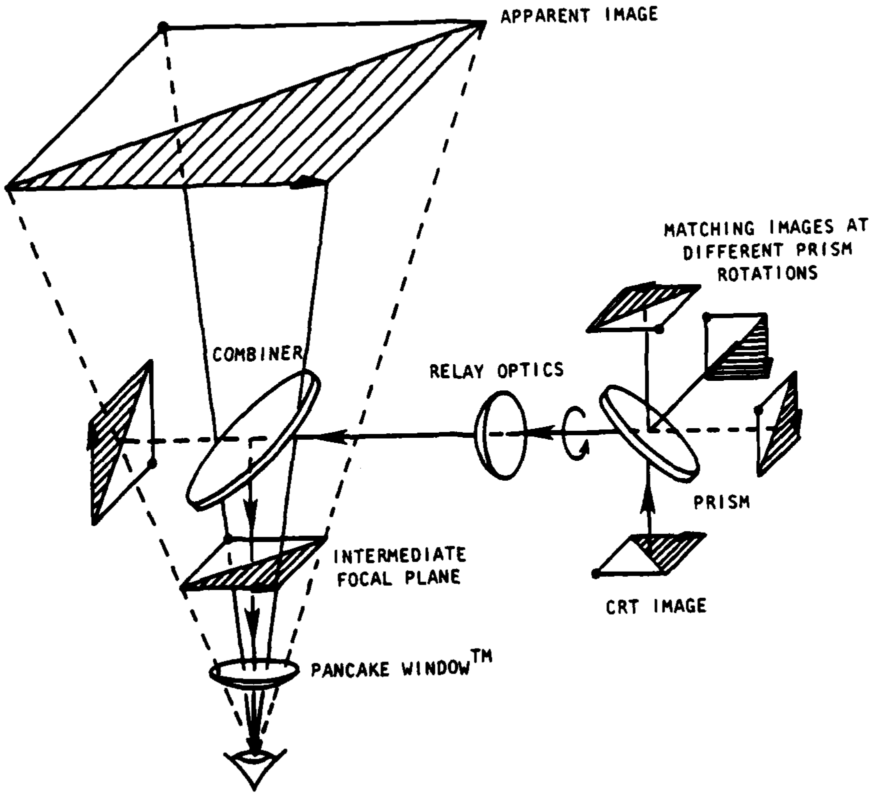


Figure 6. Image orientation through the optical system.

3.7. Image Mapping on the CRT

3.7.1. Lens Distortion

The optical system derived by Farrand uses a fiberoptic faceplate with a concave output curvature of 150 mm. This can complicate our definition of distortion. What is of concern here are the image dimensions on the input side of the CRT; that is, the image that must be introduced into the optical system. Farrand properly computes this distortion with a computer program called ACCOS, and it has been verified for this report with one called GENII. Our subsequent analyses with the CODE V program computed distortion differently. Therefore, the results shown in Figure 14, Section 4, for distortion are not the same as those for computer-generated imagery purposes and are properly ignored in favor of tabular results shown in Table 4, Section 4.

Under normal conditions, that is, with a rotationally symmetric optical system (which means that the object and image are parallel and perpendicular to the optical axis), ideal or Cartesian mapping exists when $r = f \cdot \tan\theta$. The factor r is the radial distance off the optical axis of an image point corresponding to an object point that subtends an angle θ with respect to the optical axis passing through the entrance pupil. The factor f is a constant of proportionality called the focal length. The object is assumed to be far away relative to the focal length, but similar equations apply for nearby objects.

It can be shown that for a rotationally symmetric optical system, deviations from this rule will follow the requirement that terms containing the third power, fifth power, seventh power and so on of the field angle must be the only precise description of the error. Therefore,

while even-powered terms can be used in an effort to do a curve fit, they are not inherent in the distortion function.

In the course of our study it was found that a third-order optical aberration function is insufficient to describe the distortion much beyond 30°. The problem was revealed when a distorted grid was computed that had 16% negative distortion at the sides of a square field. When the plot was extended to include the corners of the field, they actually curved back over the original grid when only the cubic, third-order distortion term was used. Obviously, the image in a rotationally symmetric optical system is single-valued so that such behavior cannot occur. This lead us to consider the logical progression of the higher order terms in a lens.

An example is set by fisheye lenses, which are intended to follow an image formula, $r = f \cdot \theta$, where now θ is measured in radians instead of degrees, and f is the focal length. This is probably the only lens readily available for the inspection of a naturally occurring form of distortion that can be calculated to a very high order.

Distortion is the difference between the Cartesian mapping and the fisheye (often called f-theta or equidistant) mapping, i.e.,

$$\text{distortion} = -\frac{1}{3}\theta^3 - \frac{2}{15}\theta^5 - \frac{17}{315}\theta^7 - \frac{62}{2835}\theta^9, \text{ etc.}$$

$$= D_3\theta^3 + D_5\theta^5 + D_7\theta^7 + \ldots.$$

A curve fitted to the seventh order term of this series fits the distortion of a ±40° display to within a small fraction of 1%.

The Farrand design has a focal length of 13.67 mm and has the distortion characteristic of a fisheye lens, as shown in Table 4. It is necessary for the computer-generated imagery to compensate for this lens

distortion. AFAMRL has proposed an equation of the form,

$$r' = c_2 r + c_3 r^2 + c_4 r^3,$$

where the coefficients are adjustable.

3.7.2. Perspective Distortion

Perspective distortion is not really a distortion at all, but simply the wrong way of looking at things. It is familiar to most of us as "keystone distortion" when we tip our cameras upward, and "wide angle distortion" when we look at the off-axis detail in an enlargement of a wide angle image. The first corresponds to a tilt of the image plane relative to the object plane, and the second is caused by shifting from the original center of perspective, which should coincide proportionately with the location of the lens relative to the film when the image was originally recorded.

Only "keystone" distortion is of concern in the display, although shifted centers of perspective could easily be included. Indeed, the latter would occur unless the displays were set for infinity (zero diopter) focus.

This occurs because the monocular displays have their optical axes tilted outward from between 10° to 30°, while our eyes look nominally straight ahead. Instead of seeing two magnified images of the CRTs straight ahead, what we see can be described as two walls tilted 20° to 60° relative to each other. Therefore, the information presented on these CRT screens must be modified to "look right" when viewed straight ahead. Fortunately, if this is done, the proper perspective occurs when the eyes pivot left and right.

Artistic perspective is generally an aesthetic construction and not accurate for our needs. The deficiency lies in the artist's finding his "vanishing points," that is, where parallels are to converge on the horizon. He chooses these because they "look nice," not because they are proper. In particular, he often applies the rules of two-point perspective when he should be using three-point perspective, presumably because he does not understand how to find a vanishing point that does not lie on the horizon.

Figure 7 shows how the horizons for lines lying on any and all tilted object planes are easily found for any screen orientation.

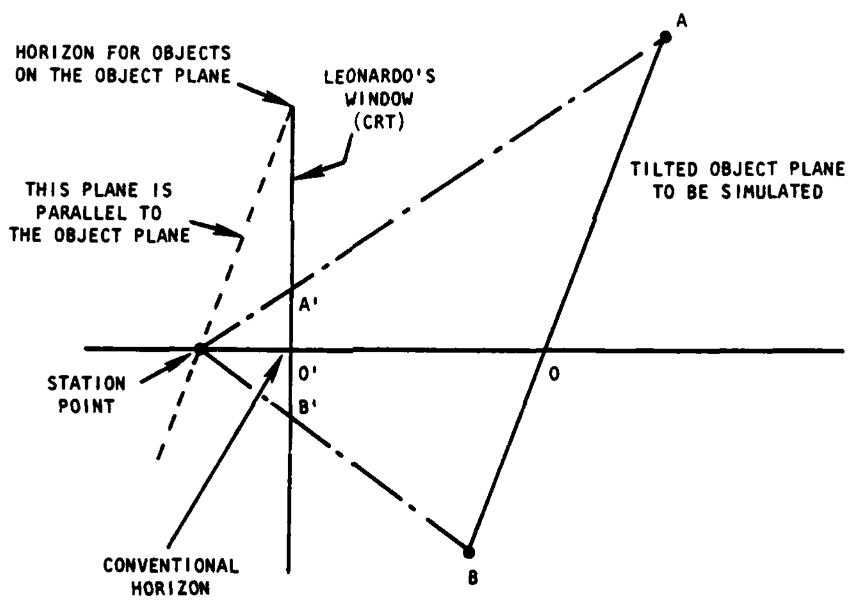


Figure 7. Method for determining correct perspective for a randomly oriented object plane.

Invoking the artist's language, there is a single "station point," which is our eyepoint or exit pupil in the display. The "easel," called "Leonardo's window," is the magnified image of the CRT faceplate. A conventional horizon (of the earth) is obtained by the intersection of a

level plane, drawn through the station point, with the easel. Since objects and separations that are extremely far away appear vanishingly small, it follows that all planes parallel to this original plane must converge in a single line, called the horizon, and that all sets of parallel lines on each plane will appear to converge to different points along the horizon. These are termed "vanishing points." But what about all the other possible planes other than the one level to the earth? Each set of parallel planes has its own horizon and is found in the same way. While a cube will have just three vanishing points for random orientation, a general six-sided solid will have six horizon lines and six vanishing points. Clearly, the problem, while now fairly obvious, is still not easy.

Figure 7 indicates how to compensate for the tilted CRT so that when viewed straight ahead it will look proper. A point-by-point transformation can be done once it is understood that the transformation is linear when the optics are corrected for their own distortion.

Since the Farrand display has optical distortion as well as perspective distortion, the computer-generated and electronics-modified imagery must compensate for both. A computer program called GRIDS was written to illustrate the effect with a uniform square grid. The program first computes the effect of optical distortion (following the equations $r = f \cdot \theta$ to generate negative or barrel distortion, and $r' = f(2 \cdot \tan\theta - \theta)$ for positive or pincushion distortion) on the grid, then performs the linear transformation.

The patterns that should be generated on the CRTs to see a flat, uniform grid image with the Farrand VCASS are similar to those shown in the middle of Figure 8. These patterns were prepared for a collimated,

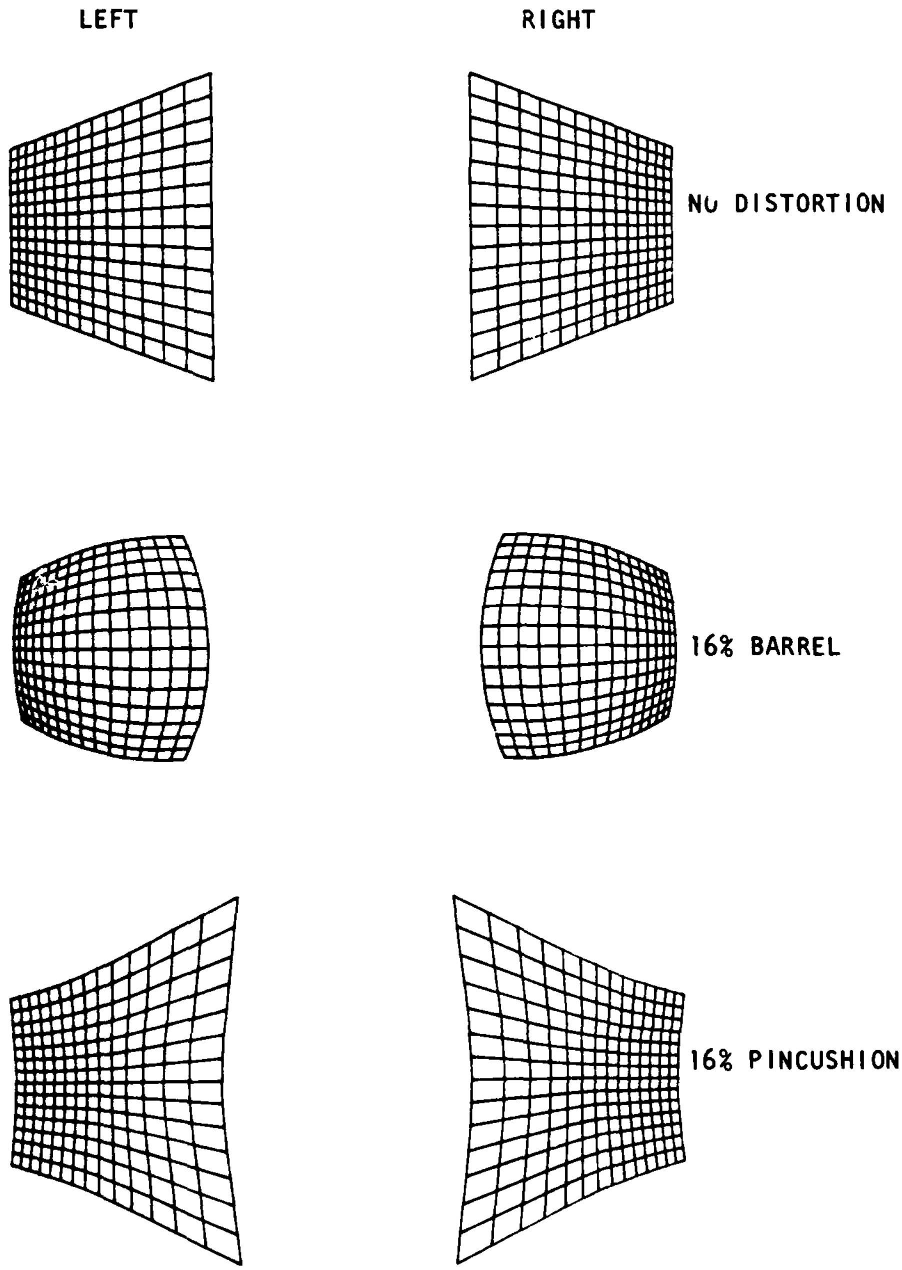


Figure 8. CRT displays with perspective compensation (20^{o} tilt of optical axis).

zero-diopter image, with the display axes tilted 20°, and for a square grid 80° on a side. The patterns were originally designed for our own experimental apparatus, which has a focal length of 38.1 mm, whereas the VCASS has a focal length of 13.67 mm. In principle, transparencies can be made from these plots and back illuminated for use on the actual Farrand display.

If the plots are reversed left for right, it is possible to gain insight into noncompensated CRT images. If a uniform square grid is displayed on the CRT, an image like the top pair reversed occurs. The purpose of predistorting the CRT with the patterns as shown is to cancel out this effect. Now, if in addition the display requires barrel or negative distortion, like the Farrand VCASS, a uniform square grid will look like the image pairs at the bottom of Figure 8, reversed. Therefore, the middle pair is generated to cancel out this effect. A lens that forms a barrel-shaped image will produce an image that looks like a pincushion when used as a magnifier.

3.7.3. False Stereo Cues

If no compensation is made for the two types of distortion in this display, an illusion of a curved image occurs. It appears that, overall, pincushion distortion plus the kind of perspective distortion obtained by tilting the displays outward will generate the illusion of an image sphere centered on the viewer's head. The perspective cues are inappropriate for the case of barrel distortion, which would be required to generate the illusion of a sphere convex toward the observer. The perspective cues are for an object distance of 1/2(IPD)/sin(tilt), where IPD is the interpupillary distance. The curvature cues depend on the degree of optical distortion, so

the strength of the illusion can vary, depending on phenomena termed "the horopter" and "Panum's area."

By reference to Figure 9 it can be shown that optical distortion permits a flat projection, as on our CRT, that gives proper cues to the curvature of a sphere curved toward our head. The intersection of the dashed lines from P must define points on the sphere by their intersection on the tangent plane, our CRT. There must be a positive distortion to get the curvature cues. The distortion we need is equal to SAG times the tangent of angle a. Working this out as a series, one obtains the SAG = $r^2/2R + r^4/8R^3 + \ldots$, and tangent of angle a is exactly r/R. Thus, the distortion required is of the form, $D_1r^3 + D_2r^5 + \ldots$.

As shown in section 3.7.1, this is the same form followed by optical distortion, so the effect of optical distortion is to create the projection of a spherical surface onto the flat CRT screen.

The influence of shifting the eye from P to its proper location in the exit pupil is shown by the longer dashed lines in Figure 9. Because the line to the right side is shorter, we see that section with higher magnification, whereas the section to the left is seen with lower magnification. These are the cues that tell us the original sphere is tilted, or that we have moved our head to the right. The cues produced for the other eye are mirror images of these cues. Except for the overlap of the two image fields, there are no true stereo cues; however, the mind is perhaps willing to extrapolate beyond the overlapping area, so that the illusion is one of having the entire image of a grid lying on a curved sheet concentric with the viewer's head. These effects should not occur when the optical distortion and improper perspective are compensated.

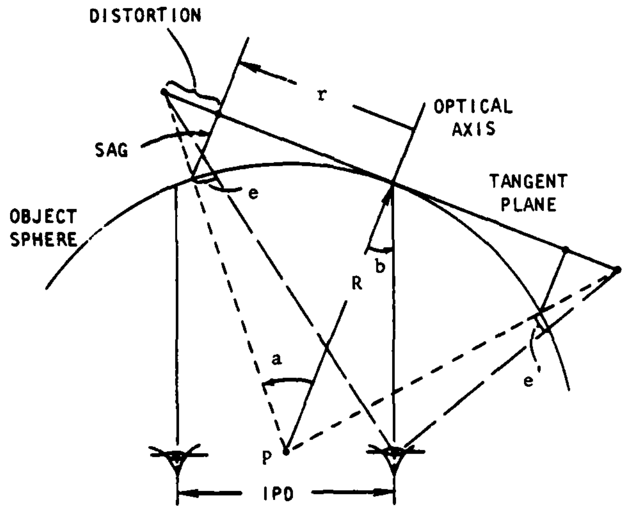


Figure 9. Distortion and perspective error produce stereoscopic cues for a sphere.

4. FINAL DESIGN

4.1. General Layout

Figure 10 shows three views of the final design. Figure 11 is a simplified equivalent optical layout of the optical path for one eye. Figure 12 shows representative ray paths through an equivalent unfolded optical layout. The figure illustrates a system without vignetting, but up to 50% vignetting is permitted for the ±40° ray bundles. The same figure shows how rays traverse the optics when a 6-mm diameter pupil, representative of what the viewer's pupil may actually be, is decentered by the maximum amount possible before it begins to exceed the maximum 15-mm pupil design diameter.

4.2. Optical Design

Figure 11 shows that in addition to the beam combiner, there are 11 lens elements plus a prism and polarizing filter in the relay optics. The Pancake Window™ contains a polarizer, two quarterwave plates (one of which is partially reflectorized), and a partially reflecting concave mirror. The output fiberoptic faceplate of the 19-mm CRT active diameter has been ground to a concave 150-mm radius.

Although there may be technical problems in making a small Pancake Window™, it appears the area of greatest technical difficulty lies in making the relay optics. Figure 13 shows that the design uses three aspheric optical surfaces. Table 1, which is an exact mathematical description of the optics, shows these are not simple conic aspherics, but are spheres deformed with up to eighth degree polynomial deformations. However, Farrand has already made several sets of optics to prove feasibility.

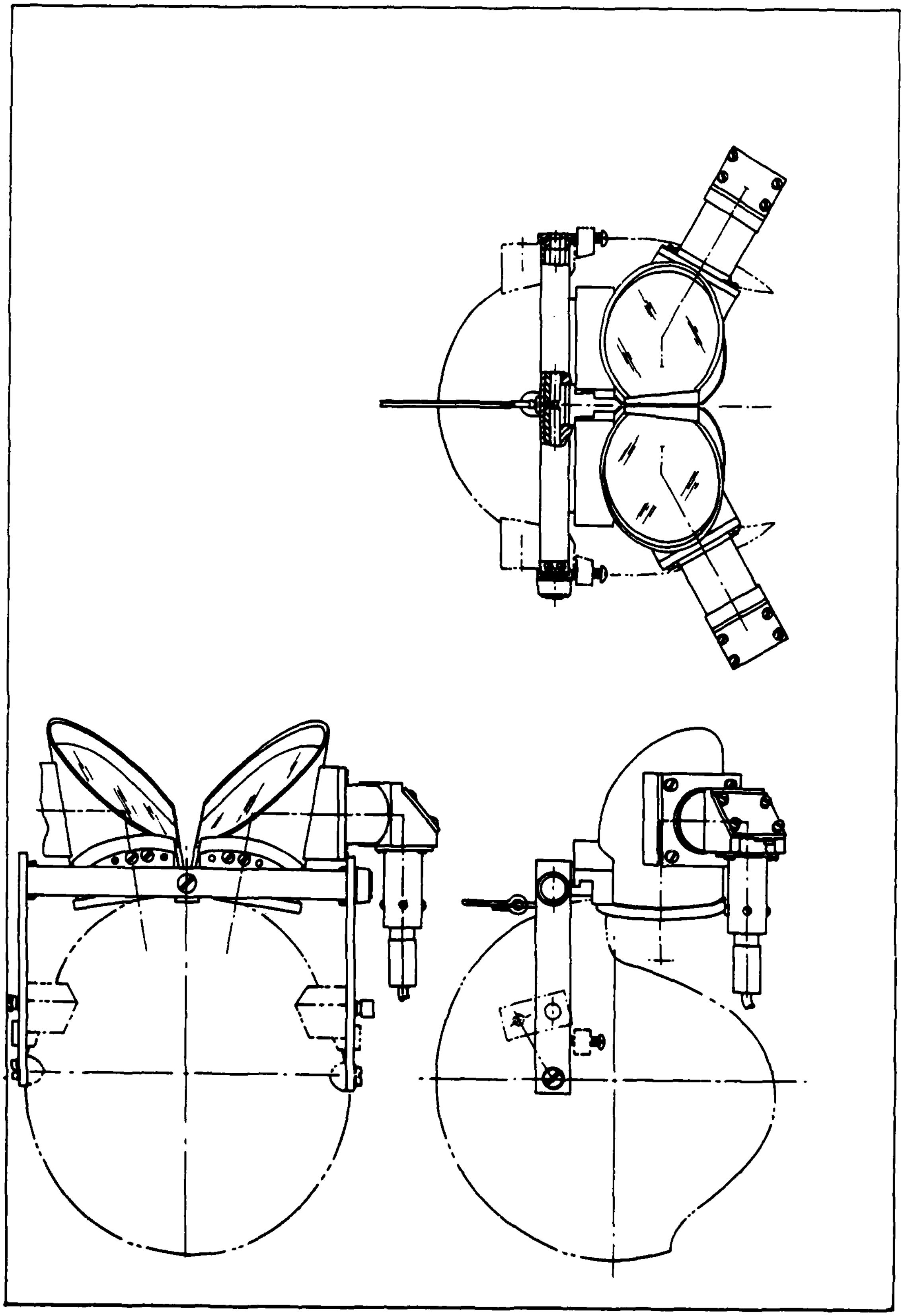


Figure 10. General layout of the Farrand VCASS.

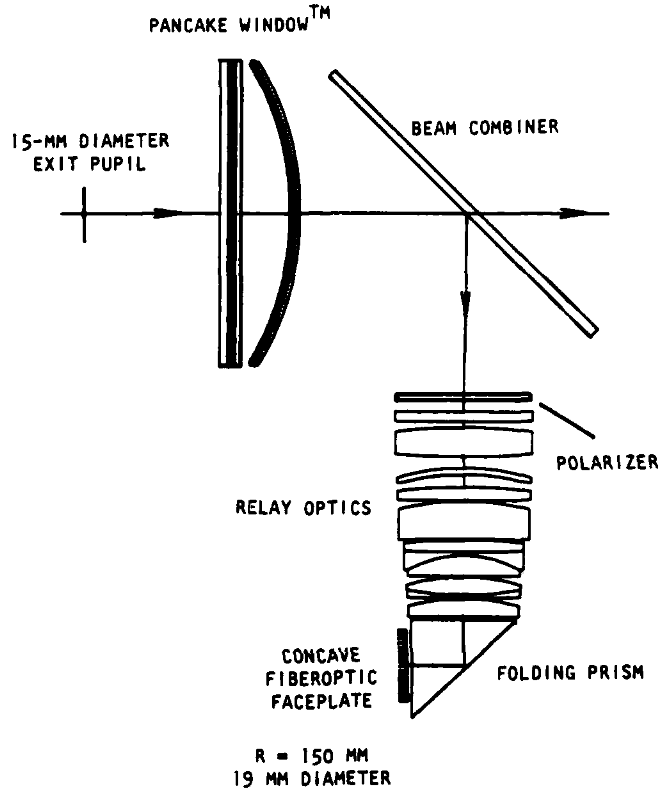


Figure 11. Representative beam combiner folding of the Farrand VCASS optical system.

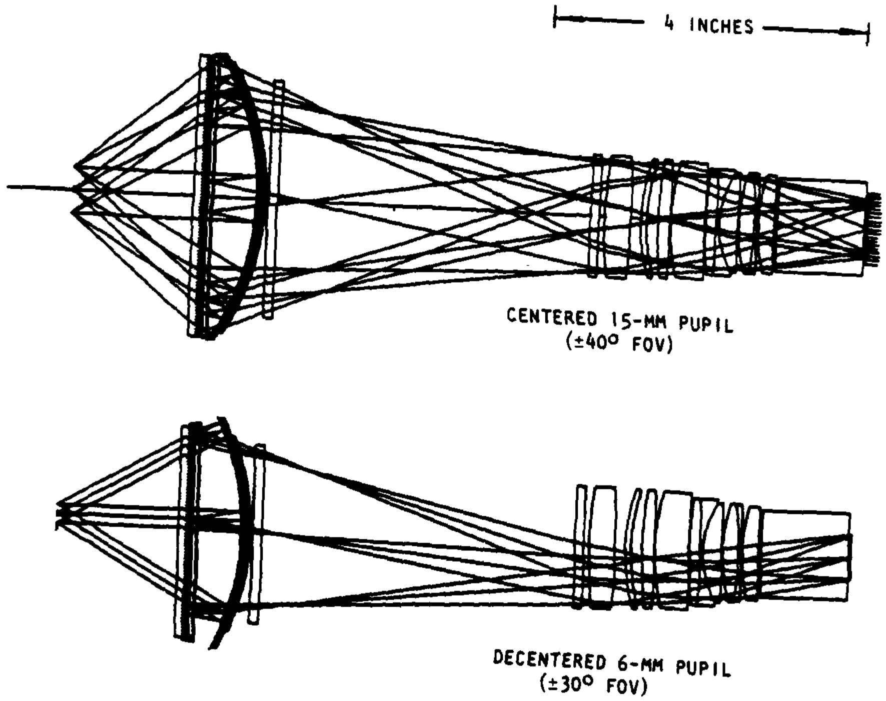


Figure 12. Selected ray paths in the Farrand VCASS design.

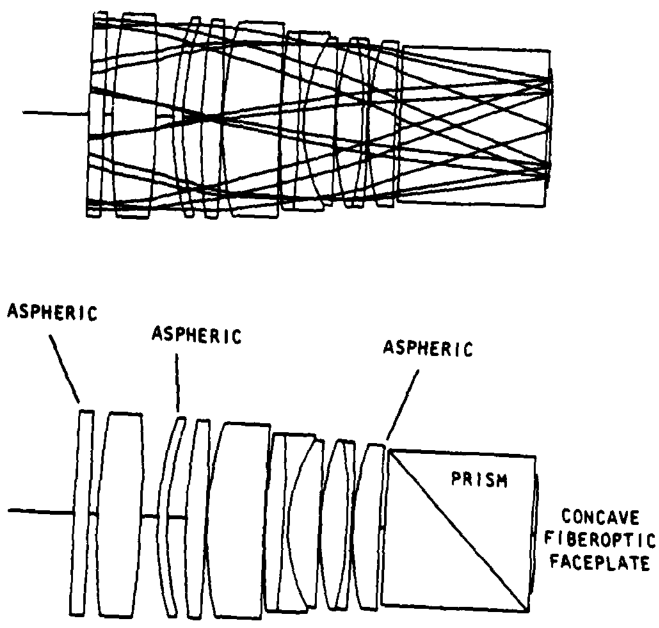


Figure 13. Details of the relay optics.

Table 1. Computerized Prescription for Farrand VCASS Optical System.

```
7/16/82
FARRAND VCASS 82

ELEMENT    RADIUS OF CURVATURE                          APERTURE DIAMETER
NUMBER      FRONT          BACK        THICKNESS         FRONT        BACK        GLASS
------------------------------------------------------------------------------------------

OBJECT             INF                  INFINITY
                                     APERTURE STOP         15.0000
                                         39.5000
   1      INF             INF             6.0000       81.2089      86.0778      K5
                                         14.0000
   2                -84.8100            -14.0000           89.1360               REFL
   3      INF             INF            -1.5000       87.9712      87.1604      K5
   3                INF                                    87.1604               REFL
   4      INF             INF             1.5000       87.1604      87.1604      K5
                                         14.0000
   5   -84.8100        -85.0000           3.0000       83.0211      83.5871      BK7
                                          1.0000
   6      INF             INF             3.0000       73.3048      71.6962      K5
                                        101.5000
   7        A(1)      -1268.4645          2.9000       36.9983      36.9400      LAKN7
                                          1.7000
   8   143.0648        -203.4505          8.4000       36.7722      35.9016      LAKN22
                                          3.3000
   9        A(2)         66.6667          1.8700       36.0675      35.7018      SF53
                                          3.6000
  10   135.1351        -883.0000          3.9000       35.7713      35.5612      LAK21
                                          0.2000
  11    72.4638         636.2993         11.0000       35.0855      32.3361      LAK21
                                          0.2000
  12   158.7302        -250.0000          3.5000       31.9577      31.1513      LAK21
  13  -250.0000          32.2581          1.0000       31.1513      29.8068      SF53
  14    32.2581       -1407.9590          6.0000       29.8068      30.0411      LAK21
                                          0.2000
  15    86.3589         -83.3333          5.1000       30.4192      30.2076      LAK21
  16   -83.3333        -302.8250          1.0000       30.2076      30.0494      SF6
                                          0.2000
  17    57.8035           A(3)            5.2000       29.4925      28.3509      LAK21
                                          1.0000
  18      INF             INF            28.4000       27.8491      19.3091      LAKN16
           IMAGE DISTANCE =               0.7617
IMAGE          -150.0000                                   22.9363
------------------------------------------------------------------------------------------

  NOTE - POSITIVE RADIUS INDICATES THE CENTER OF CURVATURE IS TO THE RIGHT
         NEGATIVE RADIUS INDICATES THE CENTER OF CURVATURE IS TO THE LEFT

       - DIMENSIONS ARE GIVEN IN MILLIMETERS

       - THICKNESS IS AXIAL DISTANCE TO NEXT SURFACE
------------------------------------------------------------------------------------------
```

ASPHERIC CONSTANTS

$$Z = \frac{(CURV)Y^2}{1 + (1-(1+K)(CURV)^2Y^2)^{1/2}} + (A)Y^4 + (B)Y^6 + (C)Y^8 + (D)Y^{10}$$

ASPHERIC	CURV	K	A	B	C	D
A(1)	0.00325000	0.000000	-3.54000E-06	-3.19000E-10	0.00000E-01	0.00000E-01
A(2)	0.01499999	0.000000	1.14000E-06	1.40000E-10	-5.00000E-13	0.00000E-01
A(3)	-0.00077563	0.000000	3.40000E-06	0.00000E-01	0.00000E-01	0.00000E-01

```
------------------------------------------------------------------------------------------
REFERENCE WAVELENGTH =        588.0 NM

SPECTRAL REGION =             486.0  -   656.0 NM
------------------------------------------------------------------------------------------

 INFINITE CONJUGATES
   EFL               =    -13.6672
   BFL               =      0.7617
   FFL               =     -4.6624
   F/NO              =     -0.9111
   IMAGE DIST        =      0.7617
   OAL               =    256.6700
   PARAXIAL
      IMAGE HT       =     11.4681
   SEMI-FIELD
      ANGLE          =     40.0000
   ENTR PUPIL
      DIAMETER       =     15.0000
      DISTANCE       =      0.0000
   EXIT PUPIL
      DIAMETER       =     43.9704
      DISTANCE       =    -39.3018
```

Starting with the optical prescription of Table 1, the Farrand design was completely reanalyzed to express the behavior of the nominal form in terms of ray aberration, wave aberration, astigmatism, distortion, and MTF. The mathematically predicted statistical performance was not modelled using Farrand tolerance data, but our own tolerance analysis indicates the optics can be manufactured to the necessary degree of quality.

Farrand apparently designed and analyzed the optics with a computer program called ACCOS. Our initial analysis was performed using a program called GENII, and our final analysis was with CODE V, the latter providing report-presentable output as well as diffraction-based MTF. The results from our two programs agree with each other, and with that from the Farrand analysis.

Table 2 is a paraxial raytrace analysis of the optical system, and enables us to obtain a generalized although approximate understanding of the path any ray can take through the system. It also provides information on local magnification and local focal lengths as well as showing whether the optical system is focussed.

Table 3 is a computed estimate of the weight of all the glass in the optical system. It shows that the pair of optics have a glass weight of about 0.9 kg. The computed center of mass is not valid because the computations are for the unfolded optical layout.

The transmission obtainable for the lens elements with single-layer magnesium fluoride coatings was computed to be 78%. This does not include the polarizing and reflective coatings. Because of the extensive use of high index glass in the Farrand design, the use of multilayer high efficiency coatings will not greatly enhance transmission from this source.

Table 2. Paraxial Raytrace of VCASS Unfolded Optical System.

SURF	Y	U	YBAR	UBAR
0	0.0000	.000000	-83909963.0000	.839100
1	7.5000	.000000	-.0000	.839100
2	7.5000	.000000	-.0000	.839100
3	7.5000	.000000	33.1444	.551137
4	7.5000	.000000	36.4513	.839100
5	7.5000	.176866	48.1987	.297527
6	5.0239	.116169	44.0333	.195422
7	4.9496	-.116169	43.7401	-.195422
8	4.6754	-.176866	43.4470	-.297527
9	2.1993	-.107770	39.2816	-.038344
10	1.8759	-.174870	39.1666	-.296293
11	1.8759	-.114858	39.1666	-.194611
12	1.5314	-.174870	38.5828	-.296293
13	1.5314	-.174870	38.5828	-.296293
14	-16.3929	-.084860	8.2128	-.189928
15	-16.6389	-.131608	7.6620	-.317621
16	-16.8627	-.033227	7.1220	-.211998
17	-17.1419	-.000000	5.3413	-.367129
18	-17.1419	.108352	4.1297	-.238526
19	-16.9392	.002213	3.6837	-.372002
20	-16.9312	.050266	2.3445	-.233536
21	-16.7352	.100842	1.4337	-.384689
22	-16.7150	.151529	1.3567	-.241806
23	-15.0482	.233435	-1.3031	-.397992
24	-15.0015	.179195	-1.3827	-.239204
25	-14.3743	.167170	-2.2199	-.227503
26	-14.2071	.152545	-2.4474	-.243740
27	-13.2919	.256296	-3.9099	-.398076
28	-13.2406	.247955	-3.9895	-.215019
29	-11.9760	.212224	-5.0861	-.200971
30	-11.7638	.414381	-5.2871	-.348730
31	-11.6809	.331493	-5.3568	-.176394
32	-9.9572	.548758	-6.2741	-.286257
33	-9.4084	.316561	-6.5603	-.165133
34	-.4181	.548758	-11.2501	-.286257
35	-.0000	.548758	-11.4682	-.286257
36	-.0000	.548758	-11.4682	-.286257

Table 3. Weight Estimated for Unfolded Optical Components.

ELEMENT NUMBER	VOLUME	SPECIFIC GRAVITY	WEIGHT	CENTER OF MASS
1	38906.59411	2.590	100.76807	3.00000
2	9967.55211	2.590	25.81596	-0.75000
4	18058.23179	2.510	45.32616	-4.15653
5	13957.60492	2.590	36.15019	1.50000
6	3100.48962	3.840	11.90588	1.56501
7	9168.94116	3.730	34.20015	4.29981
8	2264.85064	4.450	10.07862	2.38562
9	3553.07711	3.740	13.28851	2.18903
10	11001.26393	3.740	41.14472	6.15522
11	2541.21007	3.740	9.50412	1.82714
12	3409.01392	4.450	15.17011	1.87869
13	3152.21509	3.740	11.78928	3.74374
14	2598.58191	3.740	9.71870	2.69593
15	1316.46409	5.180	6.81920	-0.07632
16	3213.48093	3.740	12.01845	3.07248
17	20216.70618	4.020	81.27116	14.20000

TOTAL WEIGHT = 464.96938 GRAMS

SYSTEM CENTER OF MASS = 134.26927, MEASURED FROM THE FIRST SURFACE OF SYSTEM

4.3. Image Quality

4.3.1. Ray Aberration

Figure 14 shows the state of astigmatic and distortion correction in the design. These curves are relative to a concave 150-mm image and were obtained by tracing rays from the exit pupil back toward the CRT, as is customary. The astigmatism curves are for millimeters of defocus; this can be converted into diopters by using the lens focal length, 13.67 mm, and finding that one diopter equals about 0.185 mm. This means that the maximum tangential or sagittal defocus is less than 1/3 diopter.

Distortion as computed by this program is not completely valid for a curved fiberoptic faceplate on a CRT. Therefore, Table 4 is recommended for a proper analysis.

Table 4 compares computed image heights for the nominal design with those given by a perfect fisheye lens, following equidistant or fθ mapping. The agreement is better than 0.3%, and could be improved merely by calibrating the focal length.

Unless the aspheric surfaces, particularly the one nearest the CRT, are poorly made, or some element in the Pancake Window™ is physically or optically distorted, the actual distortion profile produced by the final display can be adjusted with the computer algorithm to almost the same precision as though the elements were made perfectly. This occurs because the distortion of a lens made with smooth curves follows a progression that is uniform despite the final magnitude of the distortion.

Figure 15 shows the results of raytraces computed in blue, red, and green light. The abscissa is the fraction or distance from the center of the pupil to which the ray aberration pertains. The ordinate has been

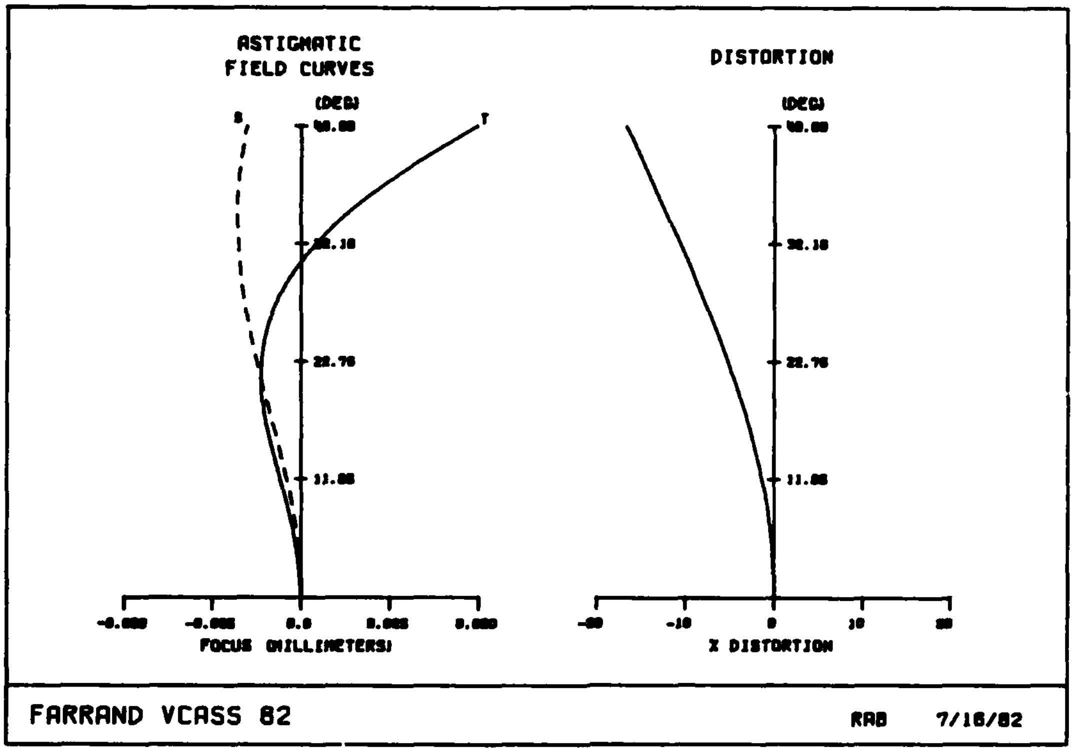


Figure 14. Accommodation and tangent plane distortion for the nominal optical design (aberration relative to 150-mm concave surface).

Table 4. Departure of the Final Design from Exact f-θ Mapping (f=13.67 mm, concave input R=150 mm).

Field angle (degrees)	Ideal image height (mm)	Actual image height (mm)	Error (%)
5	1.193	1.193	--
10	2.385	2.385	--
15	3.578	3.577	-0.02
20	4.771	4.767	-0.08
25	5.963	5.956	-0.12
30	7.156	7.144	-0.17
35	8.349	8.329	-0.24
40	9.542	9.513	-0.30

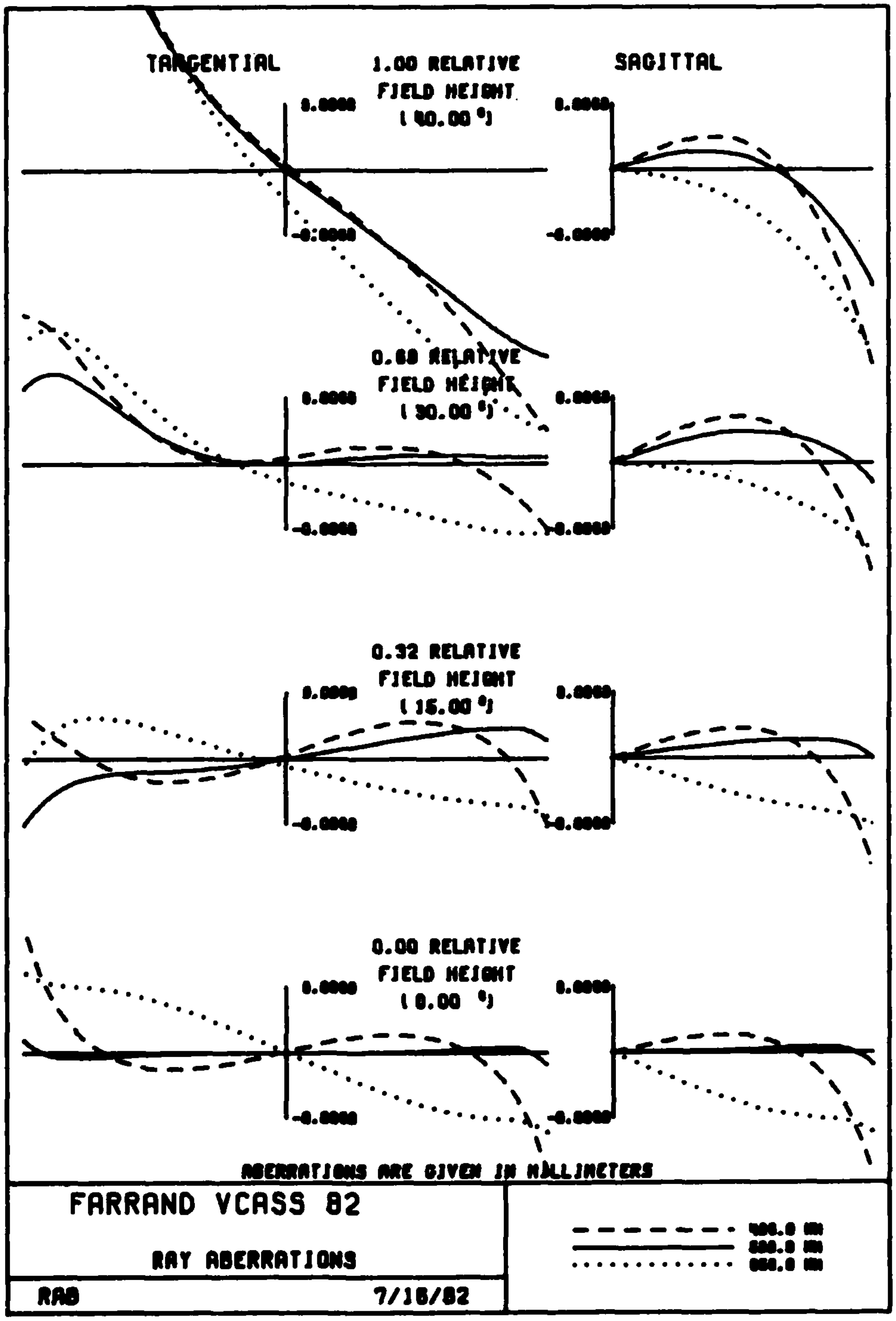


Figure 15. Raytrace analysis for full 15-mm pupil.

marked to show the magnitude of ±0.5 mrad of equivalent angular aberration. Figure 15 suggests that optical performance is starting to falter seriously at 40°. But since up to 50% vignetting has been allowed, this can be used beneficially to some degree.

These raytraces are for a 15-mm diameter pupil. However, the iris diameter or entrance pupil of the eye is about 6 mm diameter. Therefore, at any given time, the eye sees only 6 mm/15 mm = 40% of the ray fans.

4.3.2. Wave Aberration

An alternative method of analyzing images is with wave aberration or optical path difference (OPD). This method is particularly meaningful when the computation of MTF is required, since MTF correlates more directly with wave aberration. Because of the tangential flare observed in Figure 15, part of the aperture was deliberately vignetted, and Figure 16 was computed for a full 15-mm pupil. As may be seen, there is a serious amount of defocus in the tangential plane at full field. As our eye moves to one side or the other of center, a 6-mm pupil will interpret this mainly as distortion that moves with the head. The effect is no longer serious at 30° and less.

Next, let us reduce the pupil to just 6-mm diameter and expand the plot, as shown in Figure 17. The eye is perfectly centered in the display, and except at 40°, there is close to a quarterwave monochromatic quality. The image on axis is so well corrected that it does not show up on this plot scale. When the amount of wave aberration is around a quarterwave, the MTF is very high. When the wave aberration reaches a value of only a few waves, the MTF is exceedingly low.

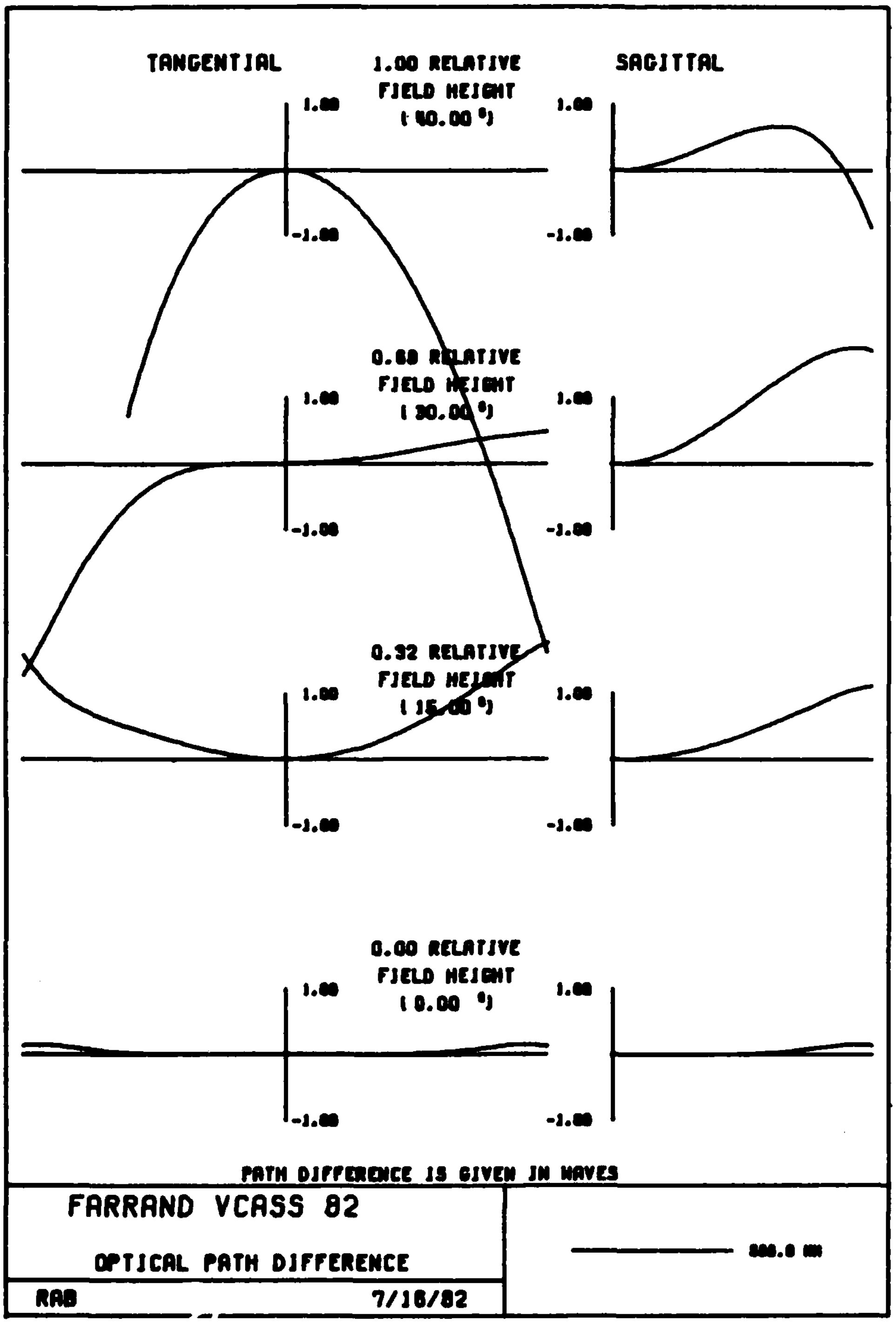


Figure 16. Optical path difference analysis for full 15-mm pupil.

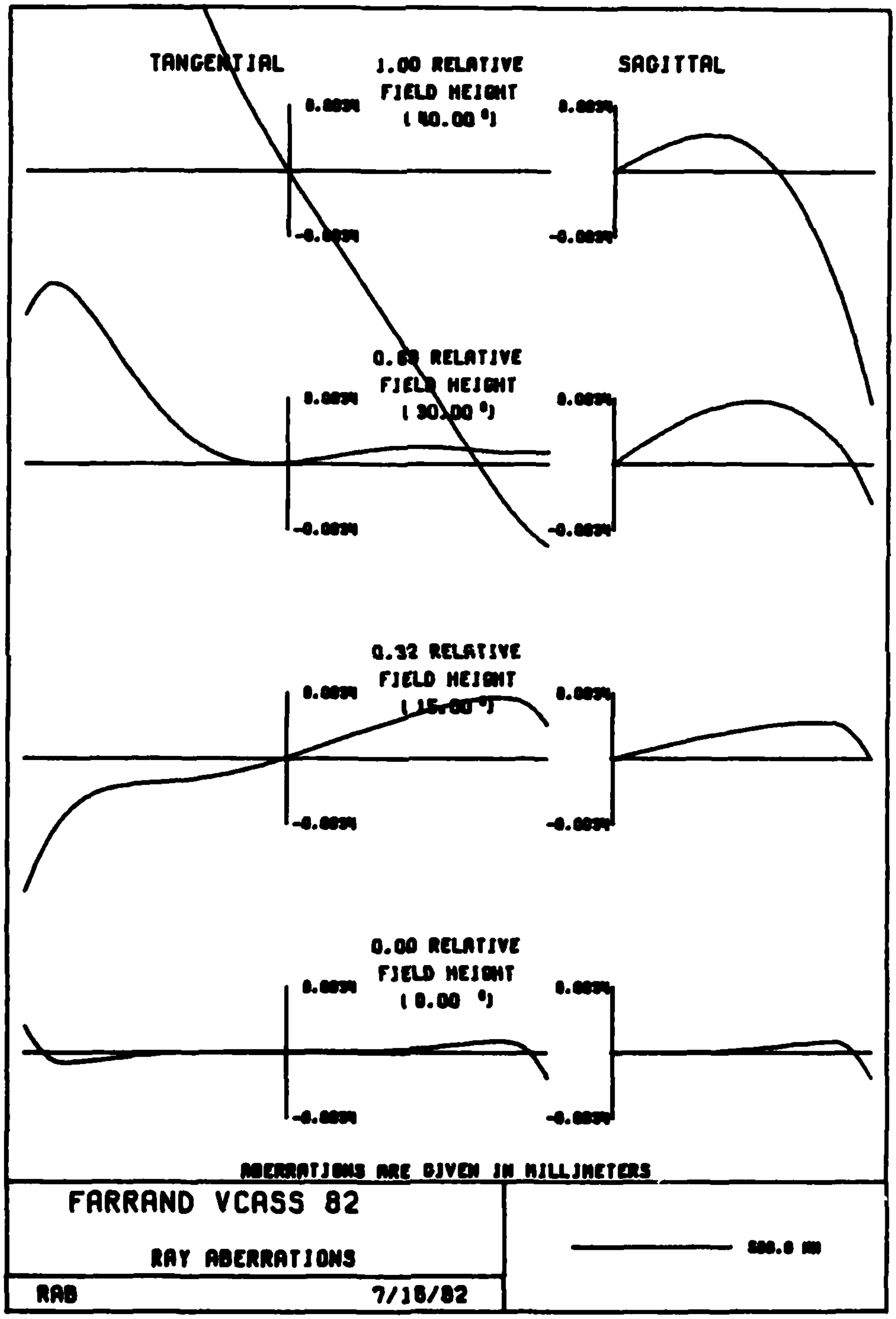


Figure 17. Ray analysis for a 6-mm diameter pupil.

Now, let us decenter the eye by 4.5 mm, which is equivalent to shifting the eye until it just starts to leave the exit pupil of the display. Figure 18 shows the computed OPD for this decentered 6-mm pupil at 30° upper and lower fields, and on the center. As is to be expected, part of the field is better than the other, and in this case the problem is that one side is defocussed a little. Nonetheless, the level of aberration is low enough that the MTF can be computed using diffraction-based methods rather than geometrical MTF. When the wave aberration exceeds approximately two waves, techniques for computing diffraction MTF can become invalid, and is one reason for interpreting the design with wave aberration.

4.3.3. MTF

MTF, sine wave response, or contrast versus frequency, are means for comparing and integrating the response of the optics with that of the CRT.

The original MTF performance specification provided a curve of MTF out to 800 cycles per raster width, for a 14.8-mm width. This is the same as 54 line pairs per millimeter, the more common method of defining spatial frequency. The Farrand design now uses a clipped round format so that its raster is closer to 19 mm, and in principle the limiting useful MTF would be at 800/19 = 42 lp/mm.

The diffraction monochromatic and polychromatic MTF for a centered 6-mm pupil diameter has been calculated with the results shown in Figures 19 and 20. The color is so well corrected that there is very little difference between them.

The monochromatic MTF for the 6-mm pupil decentered by 4.5 mm has also been computed with the results shown in Figure 21, where it has been

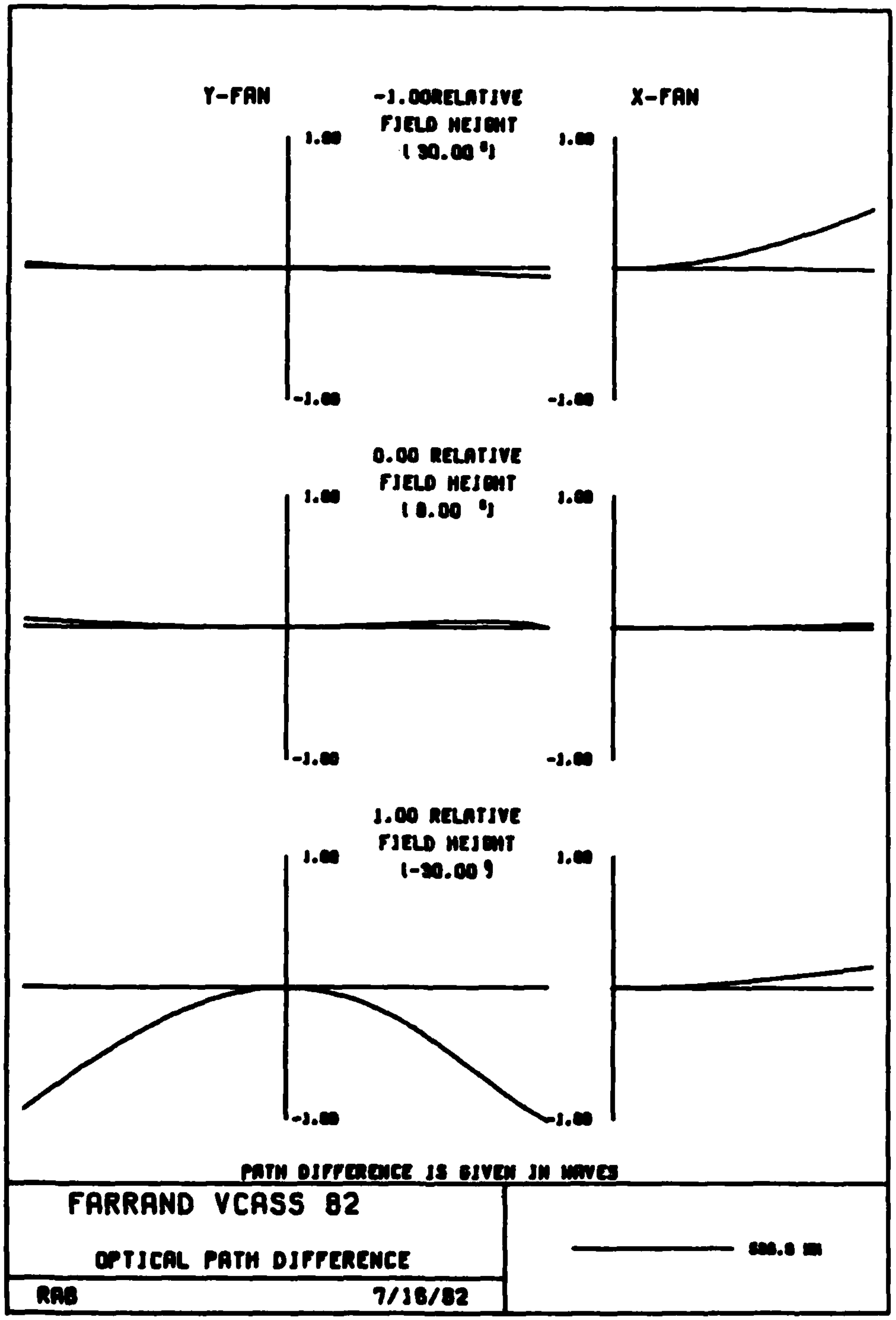


Figure 18. OPD analysis for 6-mm diameter pupil decentered 4.5 mm.

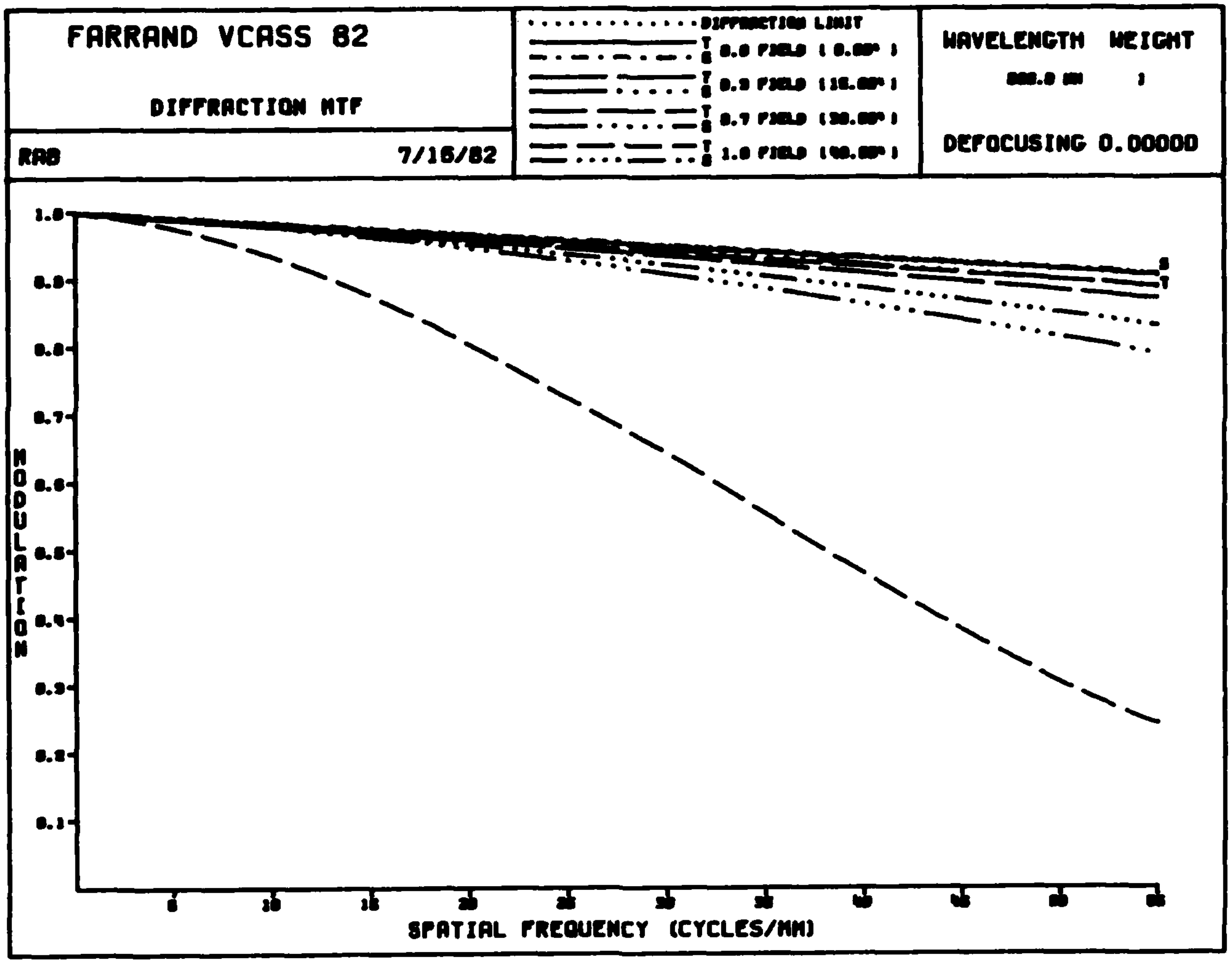


Figure 19. Diffraction MTF for monochromatic light (6-mm diameter centered pupil).

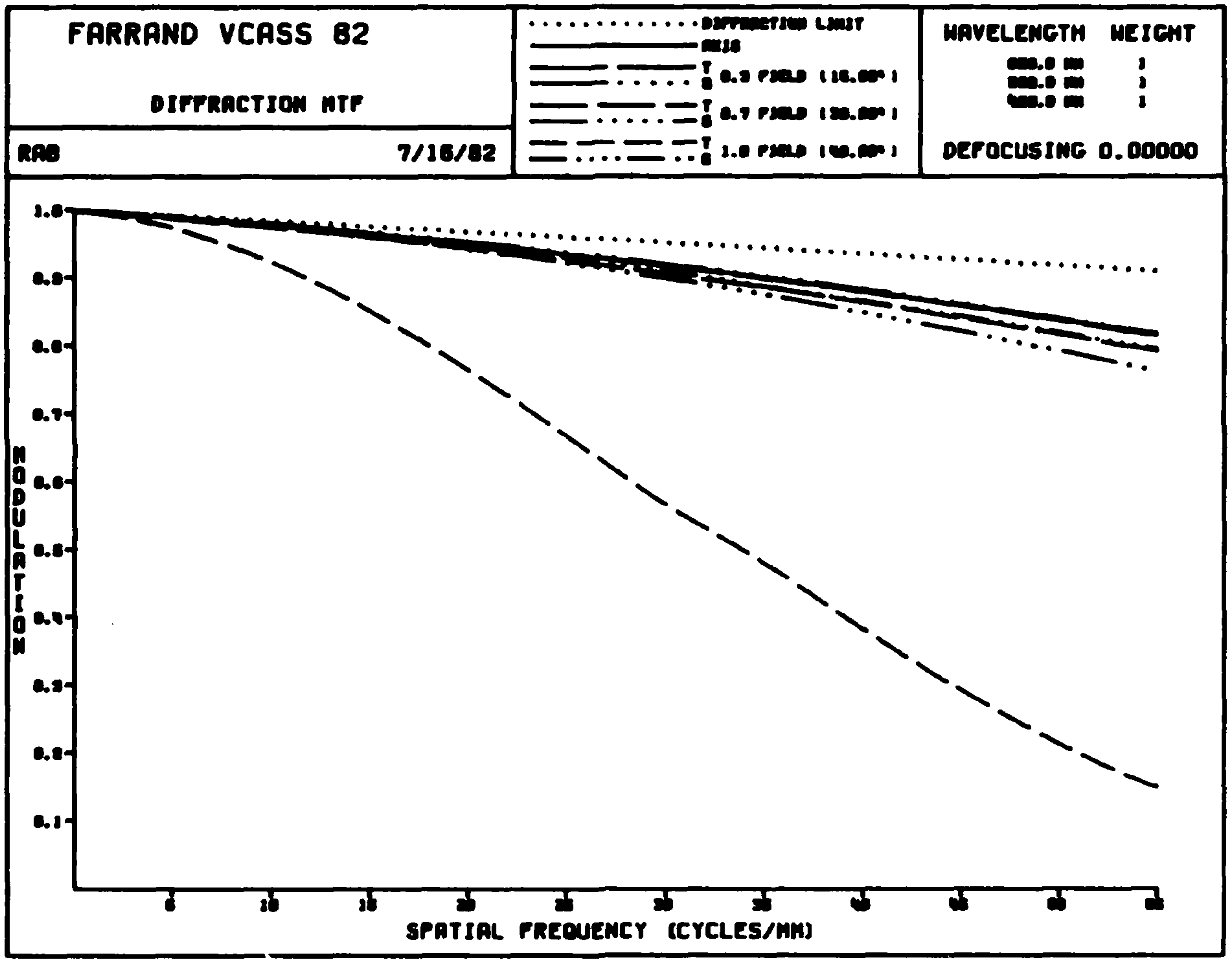


Figure 20. Diffraction MTF for white light (6-mm diameter centered pupil).

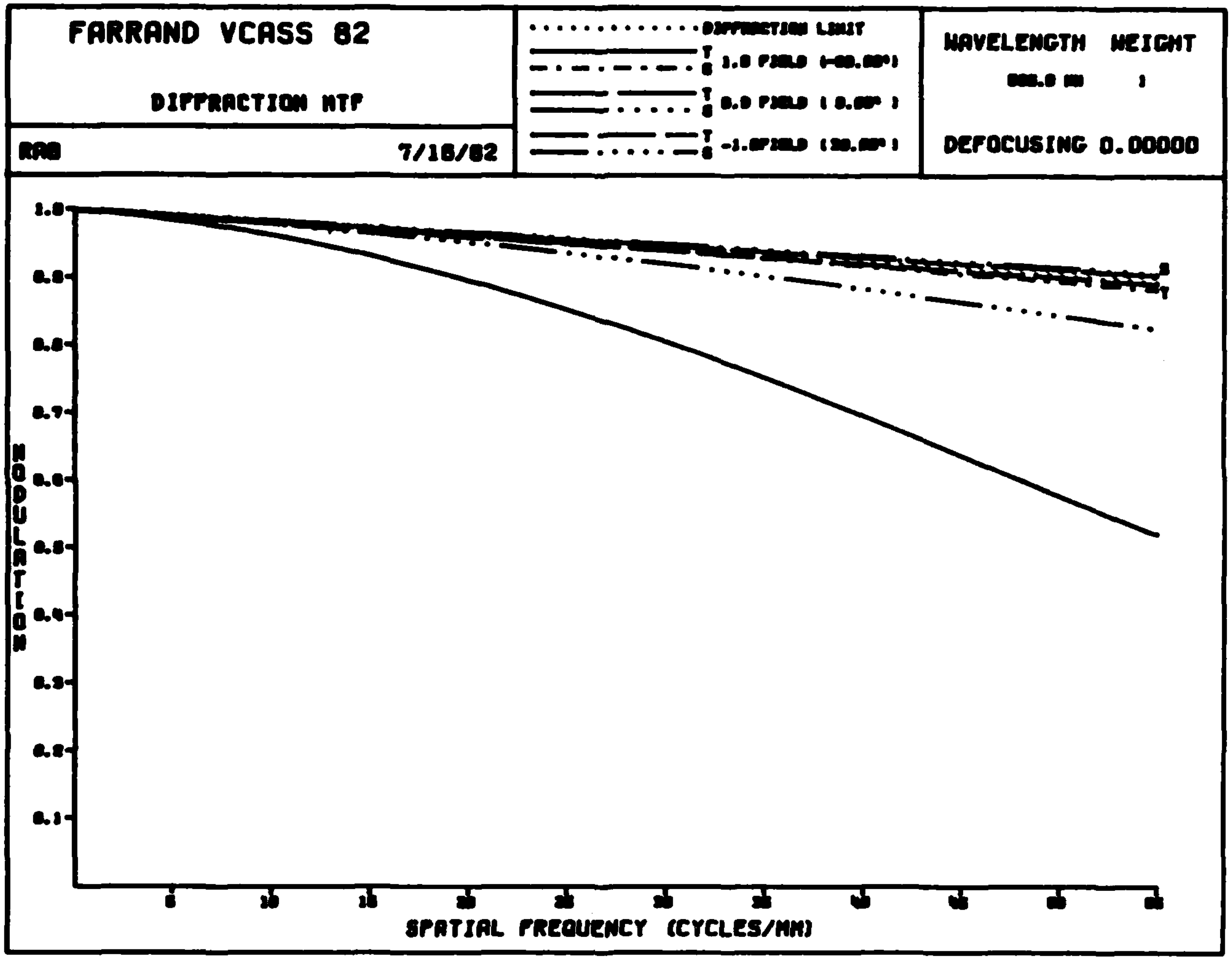


Figure 21. Diffraction MTF for white light for decentered 6-mm pupil.

analyzed, only in the plane of decentration at ±30°. Generally speaking, most of the critical performance with the display will probably occur in the central field of view, but the loss in performance at 40° is noticeable.

Now, to see whether the design meets the original MTF specification, these computed MTFs must be reconverted into the original form, which is cycles per raster width. This has been done and is represented in Figures 22, 23, and 24. The theoretical performance easily exceeds the specification on-axis and at ±30°, but just barely at 800 cycles at 40°. However, at lower spatial frequencies, it greatly exceeds the specification even at 40°. Since 800 cycles per raster width (for a width of 14.8 mm) is equivalent to more than 1600 TV lines per raster width, the optics should be significantly superior to the MTF of the CRT.

Some allowance must be made for fabrication errors, but when the difference between computed and specified MTF is as large as occurs with this design, there is generally no difficulty building the optics.

4.4. Transmission

Light transmission, as estimated by Farrand, is shown in Figure 25. Early work presumed a beam combiner with 70% reflectance and 30% transmittance, which led to a CRT path transmission of 0.6% and a see-through transmission of 2.3%. Viewing with the prototype display reveals that the CRT images are bright enough to work in a darkened simulator environment. Improvements with special coatings are unlikely to improve these values by more than a factor of two for the CRT, or more than a factor of three for the see-through condition.

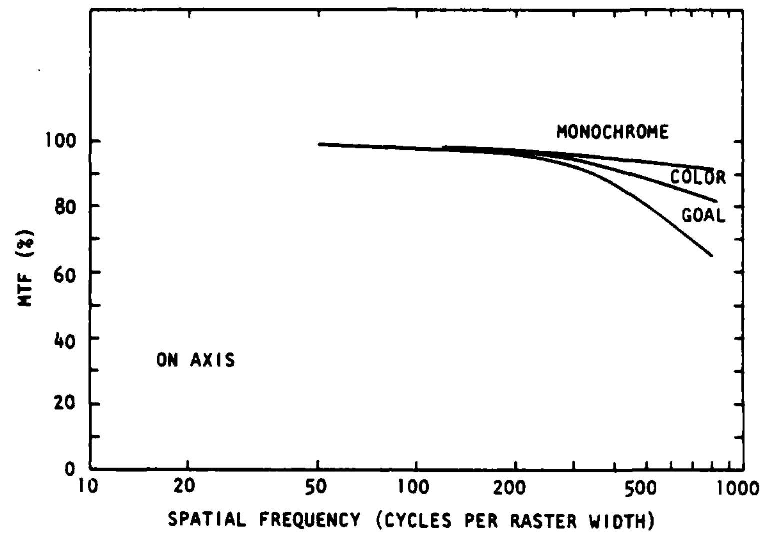


Figure 22. On-axis MTF (optics alone).

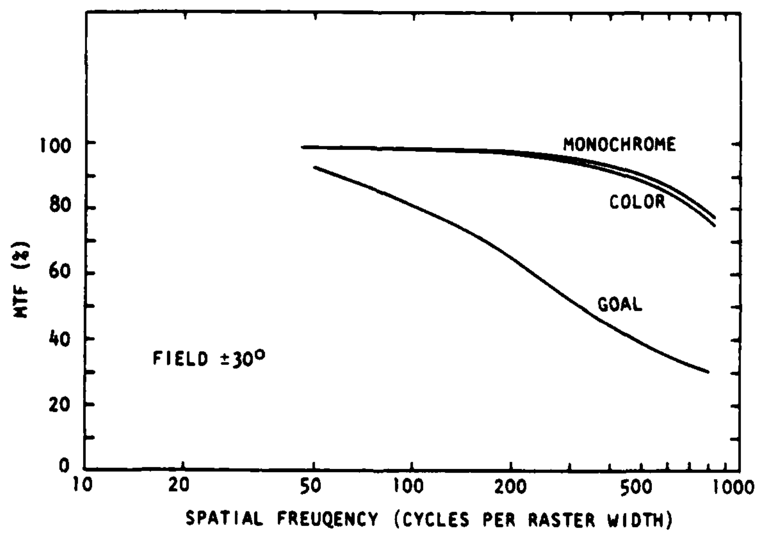


Figure 23. MTF at top and bottom of image.

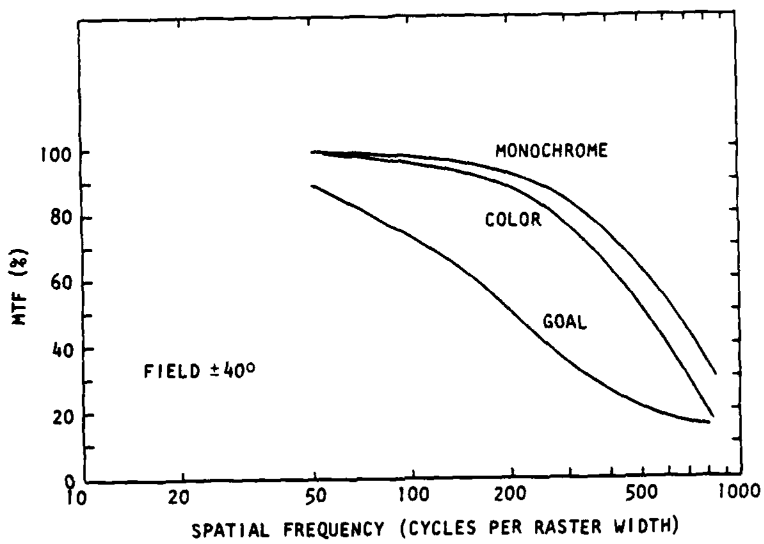


Figure 24. MTF at the sides of image.

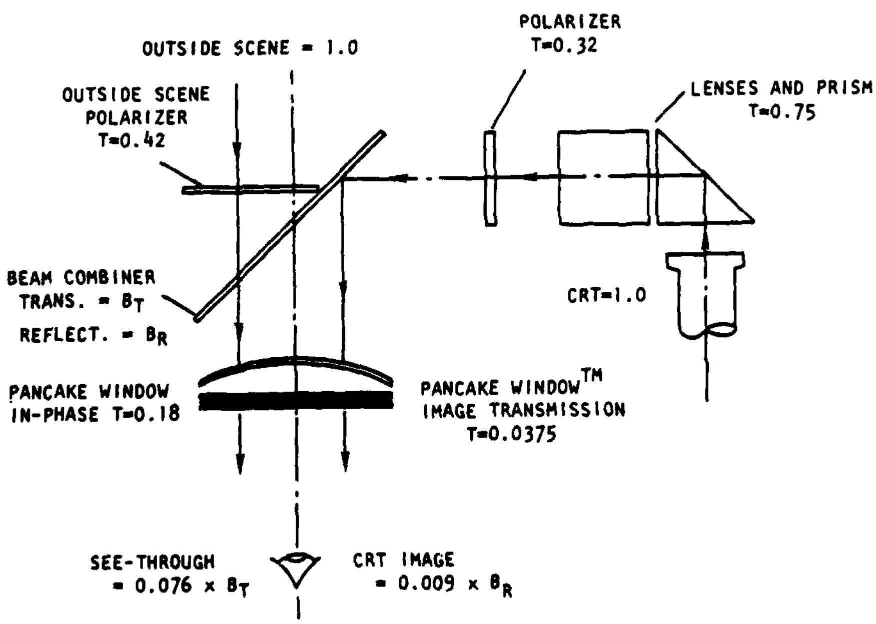


Figure 25. Light loss in the Farrand VCASS.

4.5. Ghost Images

Polarizers and synthetic quarterwave plates are not perfect, and unwanted light does penetrate the Pancake Window™. Figure 26 shows what Farrand considers to be the principal light paths, of which only the operating image is desired. Based on their experience with large Pancake Windows™ used as simple magnifiers of large CRTs, Farrand believes the intensity of these ghosts will be from 1% to 2% as bright as the wanted image. However, since we are "seeing" a small exit pupil rather than a large CRT, as in the normal application of the Pancake Window™, the concentration of light into a small area may make that 1% to 2% more apparent. Where the display image is 80° on a side, Farrand calculates that all three of the unwanted sources subtend less than 12.5°, and are similar in angular size.

Additional ghosts of the ordinary kind can occur within any complex lens system. These can be minimized with enhanced antireflection coatings if such ghosts prove to be a problem. Early observations with the prototype optical system have disclosed ghost problems with an opaque combiner.

Observations have not been made with the prototype in other than subdued light, so there are no observations regarding reflections of the eyes or other details on the face or helmet and display apparatus.

4.6. Mechanical Factors

4.6.1. Visual Obstructions

The angular subtense of optical components in the field of view must be no less than the angular field of view measured from each exit pupil, so

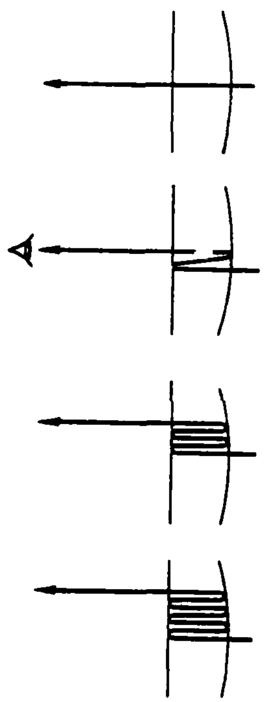


Figure 26. Light transmission in the Pancake Window™.

it is difficult to achieve large overlap of the separate images. To obtain 60°, Farrand sacrificed part of the inboard exit pupils of both halves of the display. They report that the inboard horizontal exit pupil is reduced to 5 mm at 40°. Since this vignetting occurs on the outboard side of the pupil, the viewer would have to move his head forward to center his eye on that pupil. Since this is not possible, except as a compromise when originally adjusting the display, it is conceivable in practice that the inboard fields of view will actually be clipped by a few degrees, and at least give an impression of faintness. This occurs regardless of the IPD setting or the overlap of the fields, although by initially restricting the minimum IPD and the maximum overlap, the vignetting could have been reduced as a design compromise.

A more significant obstruction is caused by the mounting fixtures of the optics. The see-through field of view (outside world as seen through the display) is smaller than the CRT field of view. There are no calculations on the difference, nor is it clear whether this problem can be readily alleviated in a modified design.

4.6.2. Materials

The use of metal is restricted because of electromagnetic interference with helmet position sensors. The entire display, except for the CRTs, is made from plastic materials. Machined parts were used for the prototypes.

4.6.3. Adjustments

There are no user adjustments for focus, so if the user wears glasses, he should wear them with the display. As we explained earlier, a dual eye display should ideally be set at zero diopters otherwise parallax exists

and dynamic distortions occur as the eyes pivot in their sockets, and as the head shifts in the helmet.

The IPD can be adjusted from 62 to 72 mm. Since the viewer will usually know his IPD, this can be set before putting on the helmet. Because of the large 15-mm exit pupils, the tolerance on IPD can be several millimeters.

The image overlap can be adjusted from 20° to 60°, and the computer-generated imagery must be changed to compensate for the perspective distortion resulting from different degrees of overlap.

Image alignment would presumably be accomplished before supplying the display to the user; however, the CRTs are reachable by hand and could, if necessary, be rotated slightly to correct for minor errors. There are several ways to collimate the two images; one way is to have centering adjustment on one of the two CRTs. It is unclear as of this writing what procedure will be used to optically align the display. Nominal centering of the display's exit pupil can be accomplished with different liner thicknesses at the top of the helmet.

Brightness disparity between the two displays will be controlled electronically, and image blending will be accomplished by means whose description is beyond the scope of this report.

4.6.4. Weight and Center of Gravity (CG)

The combined weight of the helmet and HMD, as calculated by Farrand, is 2.3 kg. The CG of the helmet and display is at $\overline{X}$ = 11.63 cm, $\overline{Y}$ = -3 cm, referenced to the helmet centerline. Since the display is symmetrical, $\overline{Z}$ is 0 cm.

Approximately 0.9 kg of the total weight is due to glass components, 0.68 kg to the helmet. Therefore, if weight reduction is to be made, it most likely must be made in the size, quantity, and materials from which the optics are designed.

5. ACCEPTANCE TEST PLAN AND TEST DATA

There is no written information from Farrand or from the Government on how the two separate halves of the display are aligned relative to each other. It is known, however, that the electronic system is capable of generating a variety of image pairs that should match when the optics are properly adjusted. Ordinarily, a binocular is tested against a single lens collimator large enough to encompass both exit pupils at once. This enables the collimation errors to be quantified. Therefore, a test method based on the testing of conventional binoculars should be applicable to the certification of VCASS.

The question of optical testing of each of the separate displays is addressed in the next paragraphs.

5.1. Exit Pupil, Eye Relief, and Vignetting

These parameters are not sensitive to fabrication tolerances, and therefore the tests need be only rudimentary to assure the absence of mistakes as opposed to errors.

The method used by Farrand consists of placing a 15-mm diameter aperture 39.5 mm behind the rear of the Pancake Window^{TM}, and then putting a 19-mm diameter reticle on a dummy curved fiberoptic faceplate. Lines corresponding to a 60° tall field are marked on the reticle, which is then back illuminated with green light.

Farrand observed that the whole input reticle area is visible over the whole area of the exit pupil except for the inboard area where it is deliberately cut off.

This is not a rigorous test because focal length has not been tested at this point. If the focal length, as will be determined from distortion-

type measurements, is in error, then the results from the present test are questionable. However, as explained, the main usefulness of this test is to look for mistakes rather than to guard against accumulated tolerances.

Assuming the test is critical, tolerances should be set, and when vignetting does occur, it should be quantified. One must be careful too that unnecessary tolerances do not force the engineers to bias the apertures of the lenses, which may lead to unsatisfactory resolution and MTF.

Farrand built three prototypes. This test was performed on all three and the 15-mm pupil at 39.9 mm was filled with no vignetting except at the inboard cut.

5.2. Transmission

A rule of photometry is that the brightness of the exit pupil is the same as the brightness of the source, less the transmission factor. Therefore, if separate measurements are made of the source and the exit pupil, the transmission is obtained as the ratio of these. Additionally, if the field of view of the light measurement device (photometer) is restricted, we can measure transmission as a function of field angle.

First, the transmission from the CRT to the eye must be measured, and then the transmission from the outside world, through the display, to the eye. For the latter, one could simply put a piece of opal glass, back-illuminated, in front of the display and take measurements with and without the display in place. It is more awkward to measure the CRT transmission.

Farrand used two methods. In the first, they removed the CRT and put

an unspecified light source with opal diffuser up to the relay* and took readings with a "Spectra Photometer" focussed on the exit pupil. They then put a light source in front of the display and took the same kind of readings to determine see-through transmission.

In the second method, they placed a 10-mm diameter aperture on the Spectra Photometer objective lens and took similar measurements looking ahead and at ±35°.

The second method is probably more meaningful than the first and the results from this method are quoted here.

For three prototypes tested without the beam combiner, the CRT transmission on-axis ranged from 0.97 to 1.07, indicating good consistency. At ±35°, there is a troublesome set of measurements ranging from 0.68 to 0.9, suggesting that possibly mechanical revisions may have been made or that the equipment may have been misaligned when tested. Testing with a full 15-mm pupil will provide more information about the pupil aberration, but it is not clear what should be done with the data. Measurements made with the small 10-mm aperture are more appropriate to vision with the eyes.

The see-through transmission measured without the beam combiner ranged around 11% to 12% and was not measured as a function of angle.

(Note that in principle it does not matter where the light source is positioned as long as it is in front of the element whose transmission is to be measured. In practice stray light can give mistaken readings.)

5.3. Field of View and Optical Distortion

The purpose of this test is to measure the amount of distortion across the field and to verify the field of view. The test is also used to obtain enough data points to find the constants for the electronic correction of fisheye distortion by means of a cubic or higher order equation. Indeed, the linear term of such a formula derives from or leads to the conventional focal length.

Farrand mounts the display on a rotary table that turns about the center of the exit pupil. The display can be turned to permit lateral and vertical measurements of its field of view. They put a reticle on a dummy fiberoptic plate at the focus of the relay, and observe the image with a fixed observing telescope, that also has an error-measuring reticle. Their fiberoptic reticle is calibrated, and they use a calibration table to interpret their measurements; however, these are conveniences and not really necessary. They compare the angles at which lines on the reticle are projected; the table permits them to determine the percent accuracy with which the optics match the design.

Farrand's measurements on the three prototype displays show agreement to within about 0.5. However, this is somewhat misleading in that a given level of precision leads to higher percentages for small field angles than it does for large field angles. The idea of using a calibrated set of lines is a convenience, but it should be remembered that a better fit to the data can be obtained simply by changing the focal length used to calculate the nominal data. That is, a "calibrated focal length" is used for best fit.

Farrand finds the inboard field of view restricted to just 36° instead of 40°, although the inboard clipping was said in the design section to yield a 5-mm pupil at the inboard 40°.

The vertical field exceeds ±40°, although it need cover only ±30°.

5.4. Field Curvature and Astigmatism

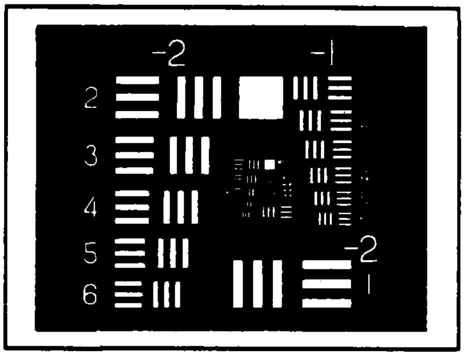
The purpose of this test is to measure the angular field curvature and angular astigmatism of the display. The test is simple, requiring a diopterscope and a resolution chart with horizontal and vertical bars. The same chart used to measure "resolution" can be used.

Farrand suggests two methods. The first is to put a pattern on the flat side of a curved fiberoptic bundle. The other is to shape a curved reticle and to put it at the focal plane. It would be easier to use the fiberoptic method with a high-resolution faceplate with 3 μm fibers.

A test pattern is shown in Figure 27 and is explained with text provided by one manufacturer, the Rolyn Company. Table 5 aids in using the pattern.

The faceplate is centered, focussed, and squared-on as well as possible. Any tilt will cause differences in the left, right, up, and down readings. Focus error is observed as a constant bias in all readings and can be subtracted if the tester is aware of its presence. Indeed, a constant diopter value can be deliberately added to each reading to see the effect of compromising focus.

The Farrand measurements are for the axis, and lateral field angles of ±38° and vertical field angles of ±30°. Errors on the order of 0.5 diopter were measured on the three prototypes, which is within acceptable bounds. We suspect from some of the measurements that the test pattern



USAF 1951 TARGET

This is the standard "Air Force" target described in Military Standard 150-A paragraph 5.1.1.7.

An Element consists of two Patterns at right angles to each other. Each Pattern consists of three lines and two spaces of equal width and length five times the width.

The change in pattern size progresses geometrically as the sixth root of two or conversely the lines per millimeter count doubles with every sixth element and these groups of six elements are referred to as a Group and assigned a group number which tells the power of 2 to which the first element in the group was raised to determine the number of lines per millimeter in that element. The zero group then has one cycle per millimeter.

The chart below enables the use of the target without computations.

Figure 27. USAF 1951 target.

Table 5. Interpretation of Pattern Resolution.

	GROUP NUMBER									
Element No.	−2	−1	0	1	2	3	4	5	6	7
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0
2	.280	.561	1.12	2.24	4.49	8.98	17.96	36.0	71.8	144.0
3	.315	.630	1.26	2.52	5.04	10.1	20.16	40.3	80.6	161.0
4	.353	.707	1.41	2.83	5.66	11.3	22.62	45.3	90.5	181.0
5	.397	.793	1.59	3.17	6.35	12.7	25.39	50.8	102.0	203.0
6	.445	.891	1.78	3.56	7.13	14.3	28.51	57.0	114.0	228.0

was probably not squared-on in every case and the optics are probably better than the measurements indicate. On the other hand, the tangential focus, according to raytrace analysis, should deteriorate rapidly at 40°.

5.5. Resolution

Presumably the same concave-plano dummy high-resolution fiberoptic faceplate will be used for this test as for the astigmatism and field curvature test. Referring to Figure 27 and Table 5, we can examine the image through the diopterscope to see what pattern is just resolvable for both horizontal and vertical bars.

For two of the prototypes, Farrand reports a blanket 7-2 pattern, which from Table 5 is found to mean 144 lines/mm, which is about three times finer than what is needed to resolve with the complete display. The third display resolves groups ranging from 6-5 to 7-4, which means from 102 to 181 lines/mm. Despite the emphasis on modern methods of image analysis, the use of the USAF 1951 resolution target remains extremely useful, and will indicate when an optical problem exists.

5.6. MTF

Modulation transfer function, technically the modulus of the optical transfer function, theoretically holds far more information than "resolution," but requires a high degree of expertise in taking measurements. The MTF is exceedingly sensitive to focus errors and tilts of the image.

Farrand used the Ealing Company's EROS 200 MTF analyzer and slit, an indexing table to turn the display to the desired field angle, and a 6-mm aperture at the exit pupil of the display. They took measurements in 10

lp/mm steps up to 50 lp/mm, which correspond to the design requirement.

The measured MTF data for the three prototypes show considerable variability, suggesting more trouble with focusing the optics than with the quality of the optics themselves. However, it is apparent that with readings almost always above 50 MTF at 50 line pairs/mm, the optics in all three cases are excellent.

These MTFs are for a centered 6-mm pupil; it would be interesting to measure the MTF for the pupil decentered a few millimeters to simulate a slightly misaligned head.

6. FEASIBILITY OF DESIGN ENHANCEMENT

6.1. Exit Pupil

Provided the exit pupil is allowed to vignette at the larger fields of view, it can be enlarged in a design of this kind simply by making the relay optics larger in diameter. However, the present design would need to be recomputed because some of the lenses are so thin that they will run out of edge thickness if the aperture is increased very much.

Practical complications having to do with folding the beam for larger relay optics will occur, and the weight of the relay optics will increase faster than the square of the increase in pupil diameter. However, the present state of on-axis correction is flawless in the Farrand design, which indicates a larger pupil can be obtained.

6.2. Field of View

There are two restrictions upon the field of view. First, there is the inboard interference of the two Pancake Windows™. Second, if the display has too wide an angle, the outboard side of the field requires an infinitely long beam combiner. This occurs with a total field around 90°, so the field of view cannot be substantially increased without radical alteration of the boundary constraints. For example, the requirement for see-through transmission inhibits the design of the CRT display. If it was not necessary to see through at all, the beam combiner could be eliminated and projection could be straight in through the conventional Pancake Window™ simulator. Another design might obscure the upper half of the see-through field and find a new input in place of the present beam combiner.

6.3. Overlap of Visual Fields in Panorama

Presently the display permits a 60° overlap (10° tilt for each half), but it is still necessary to vignette the inboard fields. Overlap can be increased by moving the windows closer to the eye; however, the distance to the eye is already 39.5 mm. If the user wants to continue to wear glasses, changes in the design will be affected by practical limitations. It seems doubtful that the display, in its present form, can have its fields overlapped much more than they already are.

6.4. Color Correction

The Farrand design is well achromatized, but it has 11 lens elements in its relay, adding to weight and absorption. If color correction is abandoned, aspheric lenses may be used to achieve the same level of quality with 1/3 to 1/2 as many elements, and with a great reduction in weight. The use of aspherics and fiber optics should permit the relay to correct for the $f-\theta$ mapping of the present design, resulting in more convenient computer-generated imagery.

Lateral color should be corrected by symmetrical and proportioned lens configurations.

The feasibility of extremely simple monochromatic lenses for a VCASS has been shown on page 11 of our earlier report, AFAMRL-TR-81-133, "Design of a Catadioptric VCASS Helmet-Mounted Display."

6.5. Resolution and MTF

The present Farrand design has an abundance of both resolution and MTF, which can be sacrificed for the sake of simplifying the present design.

On the other hand, when an optical design is unusually good, it implies that the field and exit pupil can be increased by reducing the MTF or resolution.

There seems to be no need to enhance the MTF or resolution of the present design. There is no use to having an optical system with finite MTF beyond the cutoff frequency of the image generator. If we did want to enhance the MTF of the present design, it would be difficult to do so.

6.6. Anaglyphic and Polarizing Displays

While it is probably possible to extend the specifications of the existing design, it might be more beneficial to spend some time exploring new ideas.

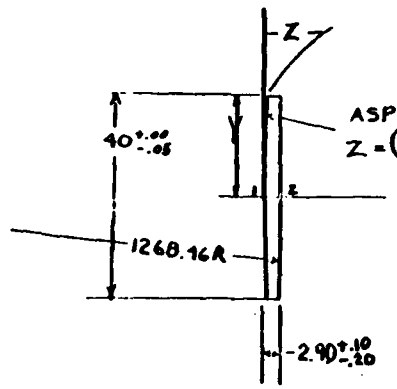
Along these lines, consider how stereoscopic motion pictures can be obtained from a single screen by using color or polarization to separate the images when they reach the eyes.

Consider also that the limits on image overlap are set by having to think in terms of a single, rotationally symmetrical optical design for each half of the display. What can we do with deliberately off-axis optics, including holographic elements? There may yet be much to learn in the development of wide angle helmet-worn simulators.

APPENDIX

FARRAND PROTOTYPE CONSTRUCTION DRAWINGS

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	



ASPHERIC CONVEX R = 307.69

$$Z = \left(cy^2 / 1 + \sqrt{1 - c^2 y^2} \right) + dy^4 + ey^6$$

AXIAL RADIUS = +307.69

$C = 1/R$

$d = -3.54 \times 10^{-6}$

$e = -3.19 \times 10^{-10}$

(SEE NOTE 9)

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. ½ RING , IRREG. ¼ RING.
   2. 2 RINGS , IRREG. ½ RING.
3. SURF. QUAL 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .005 AT 38 MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1&2
7. EFL = 622.76 BFL = 620.95 FFL =
8. FA-1 = 38 FA-2 = 38
9. SAG TABLE SURFACE 1 ON SHEET 2

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE: FRACTIONS / DECIMALS / ANGLES	CONTRACT NO.		
MATERIAL: LAK N7 N_d = 1.651601 V_d = 58.52	DRAWN	RW	4-2-79
	CHECKED	MS	4/20/79
	PROJ. ENG	MS	4/20/79
FINISH	APPROVED		
	RELEASED BY		

ITEM	NEXT ASSY	REQD	
APPLICATION			

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 1 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151275
SCALE FULL		SHEET 1 OF 2

USED ON 507

X = 0.0

Y	Z
0.250000	0.0001015
0.500000	0.0004060
0.750000	0.0009129
1.000000	0.0016215
1.250000	0.0025304
1.500000	0.0036383
1.750000	0.0049434
2.000000	0.0064434
2.250000	0.0081359
2.500000	0.0100181
2.750000	0.0120867
3.000000	0.0143384
3.250000	0.0167692
3.500000	0.0193751
3.750000	0.0221515
4.000000	0.0250936
4.250000	0.0281961
4.500000	0.0314537
4.750000	0.0348605
5.000000	0.0384102
5.250000	0.0420963
5.500000	0.0459120
5.750000	0.0498500

Y	Z
6.000000	0.0539028
6.250000	0.0580625
6.500000	0.0623207
6.750000	0.0666690
7.000000	0.0710982
7.250000	0.0755992
7.500000	0.0801623
7.750000	0.0847774
6.000000	0.0894341
8.250000	0.0941218
8.500000	0.0988293
8.750000	0.1035452
9.000000	0.1082577
9.250000	0.1129545
9.500000	0.1176232
9.750000	0.1222508
10.000000	0.1268239
10.250000	0.1313290
10.500000	0.1357520
10.750000	0.1400785
11.000000	0.1442936
11.250000	0.1483822
11.500000	0.1523287

Y	Z
11.750000	0.1561171
12.000000	0.1597311
12.250000	0.1631539
12.500000	0.1663684
12.750000	0.1693571
13.000000	0.1721020
13.250000	0.1745847
13.500000	0.1767865
13.750000	0.1786883
14.000000	0.1802705
14.250000	0.1815130
14.500000	0.1823954
14.750000	0.1828970
15.000000	0.1829964
15.250000	0.1826720
15.500000	0.1819016
15.750000	0.1806627
16.000000	0.1789322
16.250000	0.1766868
16.500000	0.1739026
16.750000	0.1705551
17.000000	0.1666197
17.250000	0.1620731
17.500000	0.1568635
17.750000	0.1510308
18.000000	0.1444863

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED		

FARRAND OPTICAL CO., INC.

117 WALL ST VALHALLA, N. Y. 10595

SAG TABLE, LENS 1, SURF 1
RELAY SYSTEM

DRAWN	PW	4-2-79
CHECKED	T. S	4/10/79
PROJ ENG	T. S	
APPROVED		
RELEASED BY		

CONTRACT NO.

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151275

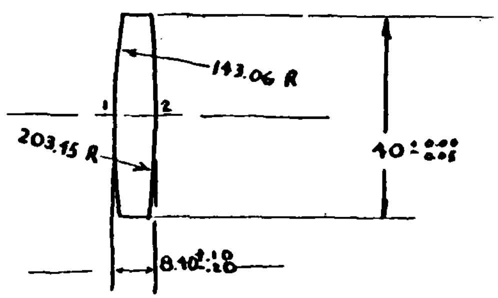
SCALE SHEET 2 OF 2

NEXT ASSY | APPLICATION | ITEM | REQD | MATERIAL | FINISH

USED ON 507

LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	

REVISIONS



NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 3 RINGS , IRREG. 1/2 RING.
   2. 3 RINGS , IRREG. 1/2 RING.
3. SURF. QUAL 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .005 AT 38 MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1&2
7. EFL = 130.25 BFL = 127.23 FFL =
8. FA-1 = 38 FA-2 = 38

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE

FRACTIONS	DECIMALS	ANGLES

MATERIAL: LAK 22
Nd: 1651129
Vd: 55.89
FINISH

CONTRACT NO.

DRAWN	Bc	4-2-79
CHECKED	M.S	4/20/79
PROJ ENG.	M.S	4/2/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

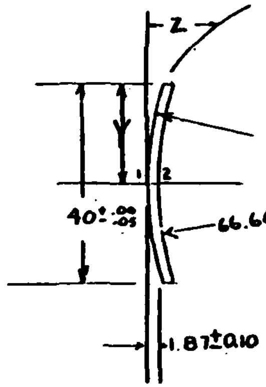
LENS 2 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151276

SCALE FULL SHEET 1 OF 1

USED ON 507

LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	3-2-79	



CONVEX ASPHERIC

$Z=\left(cy^2/1+\sqrt{1-c^2y^2}\right)+Dy^4+ey^6+Fy^8$

AXIAL RADIUS = +66.66

$C = 1/R$

$D = 1.14\times10^{-6}$

$e = 1.4\times10^{-10}$

$F = -5.0\times10^{-15}$

(SEE NOTE 9)

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1.__RING , IRREG.__RING.
   2. 2 RINGS , IRREG. 1/2 RING.
3. SURF. QUAL 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .025 AT 38. MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 2
7. EFL = 7747 BFL = 7656 FFL =
8. FA-1 = 38 FA-2 = 58
9. SAG TABLE SURFACE 1 ON SHEET 2

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: SF53
Nd=1.78301
Vd=28.69

FINISH:

CONTRACT NO.

DRAWN	TW	4-2-79
CHECKED	M.S.	4/20/79
PROJ ENG	MS 79	4/20/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 3 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151277

SCALE FULL SHEET 1 OF 2

USED ON 507

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	

X = 0.0

Y	Z
0.250000	0.0004688
0.500000	0.0018751
0.750000	0.0042192
1.000000	0.0075016
1.250000	0.0117226
1.500000	0.0168829
1.750000	0.0229834
2.000000	0.0300250
2.250000	0.0380088
2.500000	0.0469361
2.750000	0.0568082
3.000000	0.0676266
3.250000	0.0793932
3.500000	0.0921097
3.750000	0.1057781
4.000000	0.1204006
4.250000	0.1359794
4.500000	0.1525169
4.750000	0.1700159
5.000000	0.1884789
5.250000	0.2079089
5.500000	0.2283030
5.750000	0.2496823

Y	Z
6.000000	0.2720321
6.250000	0.2953620
6.500000	0.3196756
6.750000	0.3449767
7.000000	0.3712693
7.250000	0.3985574
7.500000	0.4268453
7.750000	0.4561374
8.000000	0.4864383
8.250000	0.5177527
8.500000	0.5500853
8.750000	0.5834414
9.000000	0.6178259
9.250000	0.6532441
9.500000	0.6897016
9.750000	0.7272040
10.000000	0.7657569
10.250000	0.8053662
10.500000	0.8460380
10.750000	0.8877785
11.000000	0.9305938
11.250000	0.9744905
11.500000	1.0194750
11.750000	1.0655542
12.000000	1.1127347
12.250000	1.1610236
12.500000	1.2104279

Y	Z
12.750000	1.2609547
13.000000	1.3126113
13.250000	1.3654051
13.500000	1.4193435
13.750000	1.4744342
14.000000	1.5306848
14.250000	1.5881029
14.500000	1.6466965
14.750000	1.7064734
15.000000	1.7674415
15.250000	1.8296088
15.500000	1.8929834
15.750000	1.9575733
16.000000	2.0233865
16.250000	2.0904312
16.500000	2.1587155
16.750000	2.2282475
17.000000	2.2990351
17.250000	2.3710865
17.500000	2.4444097
17.750000	2.5190125
18.000000	2.5949029

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE

FRACTIONS	DECIMALS	ANGLES

MATERIAL

FINISH

CONTRACT NO

DRAWN	P.W.	4-6-79
CHECKED	W. S.	4/26/79
PROJ ENG	W. S.	4/26/79
APPROVED	NC	
RELEASED BY		

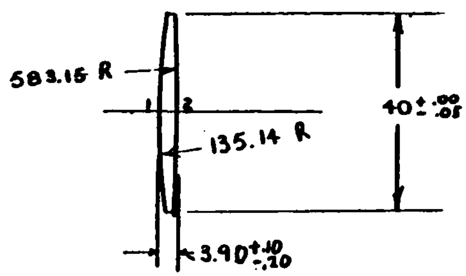
FARRAND OPTICAL CO., INC.
117 WALL ST VALHALLA, N. Y. 10595

SAG TABLE, LENS 3
SURF 1, RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151277

SCALE | SHEET 2 OF 2

USED ON 507



REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 2 RINGS, IRREG. ¼ RING.
   2. 8 RINGS, IRREG. ¼ RING.
3. SURF. QUAL. 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .025 AT 38 MM DIA.
5. BEVEL EDGES .35 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 2
7. EFL = 171.66 BFL = 169.72 FFL =
8. FA-1 = 38 FA-2 = 38

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES. DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: LAK 21
Nd=1.640496
Vd=60.10
FINISH:

CONTRACT NO.

DRAWN		5-2-79
CHECKED		5/20/79
PROJ ENG		5/10/79
APPROVED		
RELEASED BY		

ITEM	NEXT ASSY	REQD
APPLICATION		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 4 RELAY SYSTEM

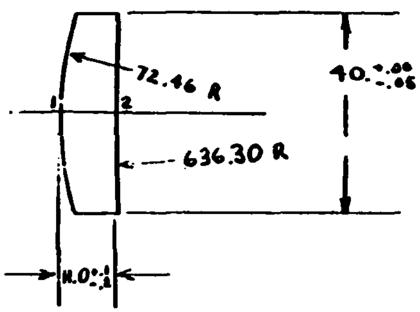
SIZE	CODE IDENT NO	DRAWING NO
A	21587	151278

SCALE FULL SHEET 1 OF 1

USED ON 507

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	



NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 8 RINGS, IRREG. 1/3 RING.
   2. 2 RINGS, IRREG. 1/6 RING.
3. SURF. QUAL. 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .025 AT 38 MM DIA.
5. BEVEL EDGES .35 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 2
7. EFL = 126.71 BFL = 119.95 FFL = -
8. FA-1 = 38 FA-2 = 38

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS | DECIMALS | ANGLES

MATERIAL: LAK 21
Nd = 1.64096
Vd = 60.10
FINISH:

CONTRACT NO.

DRAWN		4-2-79
CHECKED	M.S	4/20/79
PROJ. ENG.	M.S	4/20/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 5 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151279

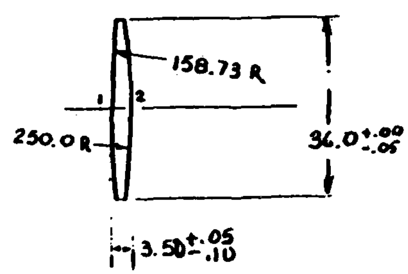
SCALE FULL | SHEET 1 OF 1

USED ON 507

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 2 RINGS, IRREG. 1/2 RING.
   2. 2 RINGS, IRREG. 1 RING.
3. SURF. QUAL. 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .005 AT 34 MM DIA.
5. BEVEL EDGES .35 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1.
7. EFL = 152.09 BFL = 150.78 FFL =
8. FA-1 = 34 FA-2 = 34



1	15287	1	
ITEM	NEXT ASSY	REQD	
APPLICATION			

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: LAK 21
Nd-1.690496
Vd-60.10

FINISH:

CONTRACT NO.

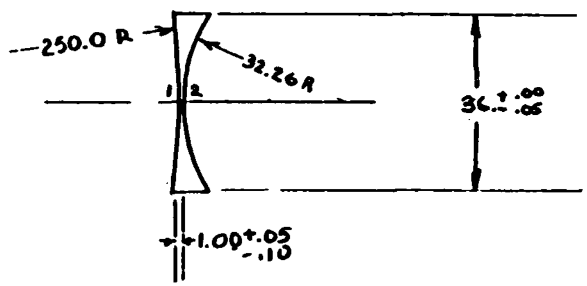
DRAWN		4-2-79
CHECKED		4/20/79
PROJ ENG		4/11/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 6 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151280
SCALE FULL		SHEET 1 OF 1

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	6-2-79	



NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 2 RINGS. IRREG. 1 RING.
   2. 2 RINGS. IRREG. 1 RING.
3. SURF. QUAL. 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .005 AT 33 MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. ---
7. EFL = -39.17 BFL = -39.24 FFL =
8. FA-1 = 34 FA-2 = 34

ITEM	NEXT ASSY	REQD
2	151287	1
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: SF53
Nd: 1.720301
Vd: 28.69
FINISH:

CONTRACT NO.

DRAWN	PW	4-2-79
CHECKED	WS	4/20/79
PROJ. ENG.	WS	4/20/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 7 RELAY SYSTEM

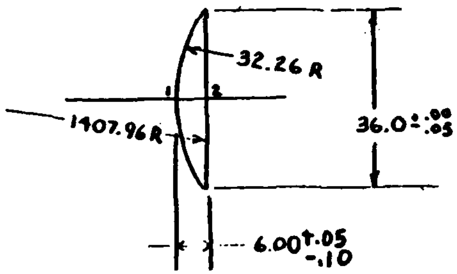
SIZE	CODE IDENT NO.	DRAWING NO.
A	21587	151281

SCALE FULL SHEET OF
USED ON 507

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	3-2-79	

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 2 RINGS, IRREG. 1 RING.
   2. 2 RING, IRREG. ½ RING.
3. SURF. QUAL. 1. 80/50
   2. 80/50
4. EDGE THICK. RUNOUT .02 AT 34 MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 2.
7. EFL = 51.46 BFL = 47.72 FFL =
8. FA-1 = 34 FA-2 = 34



2	151288	1
ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE: FRACTIONS DECIMALS ANGLES

MATERIAL: LAK 21
Nd = 1.640496
Vd = 60.10
FINISH:

CONTRACT NO.

DRAWN	PW	4-2-79
CHECKED	M.S	4/10/79
PROJ. ENG.	M.S	4/10/79
APPROVED		
RELEASED BY		

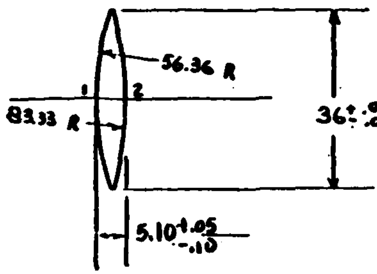
FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 8 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151282
SCALE FULL		SHEET OF

USED ON 507

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	



NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 2 RING , IRREG. 1/2 RING
   2. 2 RING , IRREG. 1 RING
3. SURF. QUAL 1. 60/40
   2. 60/40
4. EDGE THICK. RUNOUT .005 AT 34 MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1
7. EFL = 53.25 BFL = 51.37 FFL =
8. FA-1 = 34 FA-2 = 34

ITEM	NEXT ASSY	REQD
1	151299	1
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN ____ AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: LAK21
Nd=1.640496
Vd=60.10
FINISH:

CONTRACT NO.

DRAWN	PW	4-2-79
CHECKED	M.S	4/10/79
PROJ. ENG.	M.S JM	4/10/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 9 RELAY SYSTEM

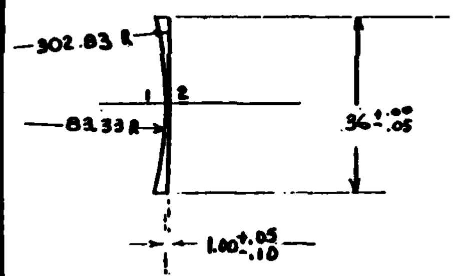
SIZE	CODE IDENT NO	DRAWING NO
A	21587	151283
SCALE FULL		SHEET 1 OF 1

USED ON 507

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 1 RING . IRREG. ½ RING.
   2. 1 RING . IRREG. ½ RING.
3. SURF. QUAL. 1. 60/40
   2. 60/40
4. EDGE THICK. RUNOUT .025 AT 15 MM DIA.
5. BEVEL EDGES ... MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 2
7. EFL = -143.07 BFL = -143.84 FFL =
8. FA-1 = 32 FA-2 = 32



ITEM	NEXT ASSY	REQD
2	151853	1

APPLICATION

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE: FRACTIONS DECIMALS ANGLES

MATERIAL SF6
Nd = 1.805182
Vd = 25.43
FINISH

CONTRACT NO.

DRAWN	PW	4-2-79
CHECKED	WS	4/10/79
PROJ ENG	WS	4/10/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS 10 RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151284

SCALE FULL SHEET 1 OF 1

USED ON 507

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-7?	

ASPHERIC CONVEX

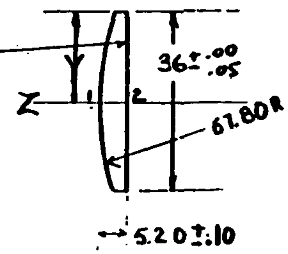
$Z = \left(Cy^2/1+\sqrt{1-C^2y^2}\right) + \alpha y^4$

AXIAL RADIUS = −1289.27

$C = 1/R$

$\alpha = 3.4 \times 10^{-6}$

(SEE NOTE 9)



NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. 1 RING . IRREG. 1/4 RING.
   2. 1 RING . IRREG. 1/4 RING.
3. SURF. QUAL 1. 30/10
   2. 30/10
4. EDGE THICK. RUNOUT .005 AT 34 MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 2
7. EFL = 86.5 BFL = 83.46 FFL =
8. FA-1 = 31 FA-2 = 30
9. SAG TABLE SURFACE 2 ON SHEET 2

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: LAK21
Nd=1.640496
Vd=60.10
FINISH:

CONTRACT NO.

DRAWN	PW	4-2-79
CHECKED	M.S	4/20/79
PROJ ENG.	YS.S	4/20/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

LENS II RELAY SYSTEM

SIZE	CODE IDENT NO.	DRAWING NO
A	21587	151285

SCALE FULL — SHEET 1 OF 2

USED ON 507

LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED		

SAG Y,31 .4? 46 .4?

SAG TABLE AT SURF 31

X = 0.0

Y	Z
0.250000	-0.0000242
0.500000	-0.0000967
0.750000	-0.0002171
1.000000	-0.0003844
1.250000	-0.0005977
1.500000	-0.0008554
1.750000	-0.0011558
2.000000	-0.0014969
2.250000	-0.0018762
2.500000	-0.0022910
2.750000	-0.0027384
3.000000	-0.0032150
3.250000	-0.0037170
3.500000	-0.0042405
3.750000	-0.0047613
4.000000	-0.0053347
4.250000	-0.0058957
4.500000	-0.0064591
4.750000	-0.0070193
5.000000	-0.0075704
5.250000	-0.0081063
5.500000	-0.0086203
5.750000	-0.0091056
6.000000	-0.0095551
6.250000	-0.0099612
6.500000	-0.0103161
6.750000	-0.0106118
7.000000	-0.0108398
7.250000	-0.0109912
7.500000	-0.0110571
7.750000	-0.0110279
8.000000	-0.0108941
8.250000	-0.0106455
8.500000	-0.0102718
8.750000	-0.0097624
9.000000	-0.0091061
9.250000	-0.0082918
9.500000	-0.0073077
9.750000	-0.0061419
10.000000	-0.0047822
10.250000	-0.0032160
10.500000	-0.0014303
10.750000	0.0005861
11.000000	0.0028527
11.250000	0.0053775
11.500000	0.0081765
12.000000	0.0146556
12.250000	0.0183657
12.500000	0.0224101
12.750000	0.0268044
13.000000	0.0315647
13.250000	0.0367076
13.500000	0.0422497
13.750000	0.0482081
14.000000	0.0546001
14.250000	0.0614435
14.500000	0.0687562
14.750000	0.0765566
15.000000	0.0848633
15.250000	0.0936953
15.500000	0.1030719
15.750000	0.1130127
16.000000	0.1235375
16.250000	0.1346667
16.500000	0.1464208
16.750000	0.1588207
17.000000	0.1718875
17.250000	0.1856429
17.500000	0.2001085
17.750000	0.2153066
18.000000	0.2312597

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE

FRACTIONS	DECIMALS	ANGLES

MATERIAL

FINISH

CONTRACT NO

DRAWN	PW	4-2-79
CHECKED	WS	4/2/79
PROJ ENG	YS	[illegible]
APPROVED	[illegible]	
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST VALHALLA, N. Y. 10595

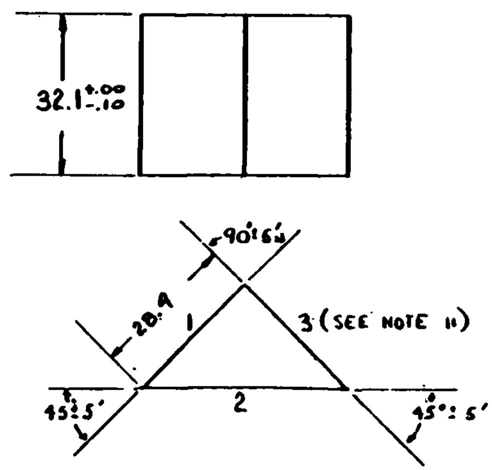
SAG TABLE, LENS
SURF 2, RELAY SYSTEM

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151285

SCALE SHEET 2 OF 2

USED ON 567

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED
A	ISSUED	5-2-79	



NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 3+1..1 RING . IRREG. ½ RING.
   2 ½ RING . IRREG. ¼ RING.
3. SURF. QUAL 1. 50/10
   2. 30/10
4. EDGE THICK. RUNOUT ... AT ... MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1 & 3
7. EFL = BFL = FFL =
8. FA-1 = 28 FA-2 = 31.5X28, FA3 = 22
9. PYRAMID ERROR NOT TO EXCEED 2 MIN
10. SURFACE 2 TO BE SILVERED AND PROTECTED WITH INCONEL & LACQUER
11. SURFACE QUALITY, SURF 3 = SURF 1. HOWEVER BEST SURF. SHOULD FACE TUBE.

ITEM	NEXT ASSY	REQD
APPLICATION		

UNLESS OTHERWISE SPECIFIED REMOVE ALL BURRS BREAK SHARP EDGES DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:

FRACTIONS	DECIMALS	ANGLES

MATERIAL: LAK N 16
Nd: 1.7335
Vd: 51.65
FINISH:

CONTRACT NO.

DRAWN	PU	4-2-79
CHECKED	M.S.	4/20/79
PROJ ENG	T.S. M	4/20/79
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO., INC.
117 WALL ST. VALHALLA, N. Y. 10595

FOLDING PRISM, RELAY

SIZE	CODE IDENT NO	DRAWING NO
A	21587	151286

SCALE FULL SHEET OF

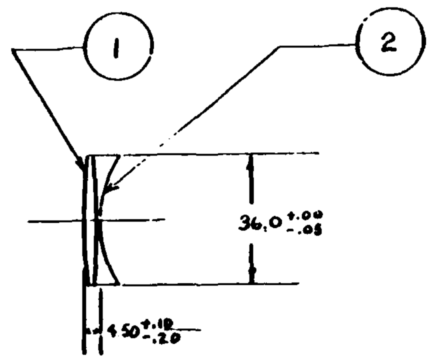
USED ON 507

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS.
2. JOIN WITH EASTMAN KODAK HE-2 CEMENT OR EQUIVALENT.
3. EFL =
   BFL =
   FFL =
4. EDGE THICKNESS RUNOUT NOT TO EXCEED .01 TIR AT 34 MM DIA

151287 | A

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
/	A	ISSUED		



1	151280	1	LENS 6 RELAY SYSTEM
2	151281	1	LENS 7 RELAY SYSTEM
ITEM	PART NO	REQ	DESCRIPTION

PARTS LIST

ITEM	NEXT ASSY	REQD
1	51299	1

APPLICATION

UNLESS OTHERWISE SPECIFIED
MATERIAL
FINISH
CONTRACT NO
DRAWN P.W. 4/10/75
CHECKED 4/.../75
APPROVED
RELEASED BY

FARRAND OPTICAL CO., INC.
117 WALL ST VALHALLA, N. Y. 10595

TRIPLET, RELAY LENS SYSTEM VCASS (PART A)

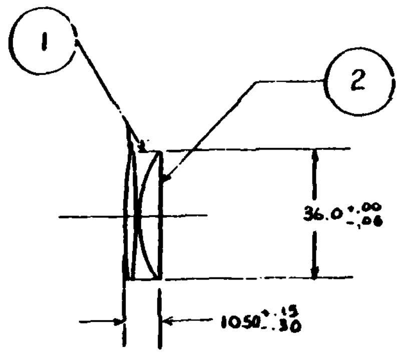
SIZE B | CODE IDENT NO 21587 | DRAWING NO 151287

SCALE FULL | SHEET OF

USED ON 507

NOTES: UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. JOIN WITH EASTMAN KODAK HE 2 CEMENT OR EQUIVALENT
3. EFL = 693.19
   BFL = 683.22
   FFL =
4. EDGE THICKNESS RUNOUT NOT TO EXCEED .01 TIR AT 34 MIN DIA



151288 | A

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	ISSUED		

ITEM	PART NO	REQ	DESCRIPTION
1	151287	1	TRIPLET, RELAY LENS (PART A)
2	151282	1	LENS B RELAY SYSTEM

PARTS LIST

DRAWN	FW	4/10/73
CHECKED	W.S.	4/11/73
PROJ ENG	W.S.	4/11/73
APPROVED		
RELEASED BY		

FARRAND OPTICAL CO. INC.
117 WALL ST VALHALLA N Y 10595

TRIPLET RELAY LENS SYSTEM VCASS

SIZE	CODE IDENT NO	DRAWING NO
B	21587	151288

SCALE FULL SHEET OF

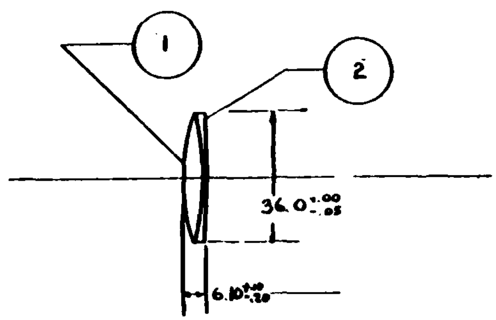
NOTES. UNLESS OTHERWISE INDICATED

1. ALL DIMENSIONS IN MILLIMETERS
2. JOIN WITH EASTMAN KODAK HE-2 CEMENT OR EQUIVALENT
3. EFL = 83.26
   EFL = 79.87
   FFL =
4. EDGE THICKNESS RUNOUT NOT TO EXCEED .01 MM AT 34 MM DIA.

151289 | A

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	ISSUED		



1	151285	1	LENS 9 RELAY SYSTEM
1	151289	1	LENS 10 RELAY SYSTEM
ITEM	PART NO	REQ	DESCRIPTION

PARTS LIST

FARRAND OPTICAL CO., INC.
117 WALL ST VALHALLA N Y 10595

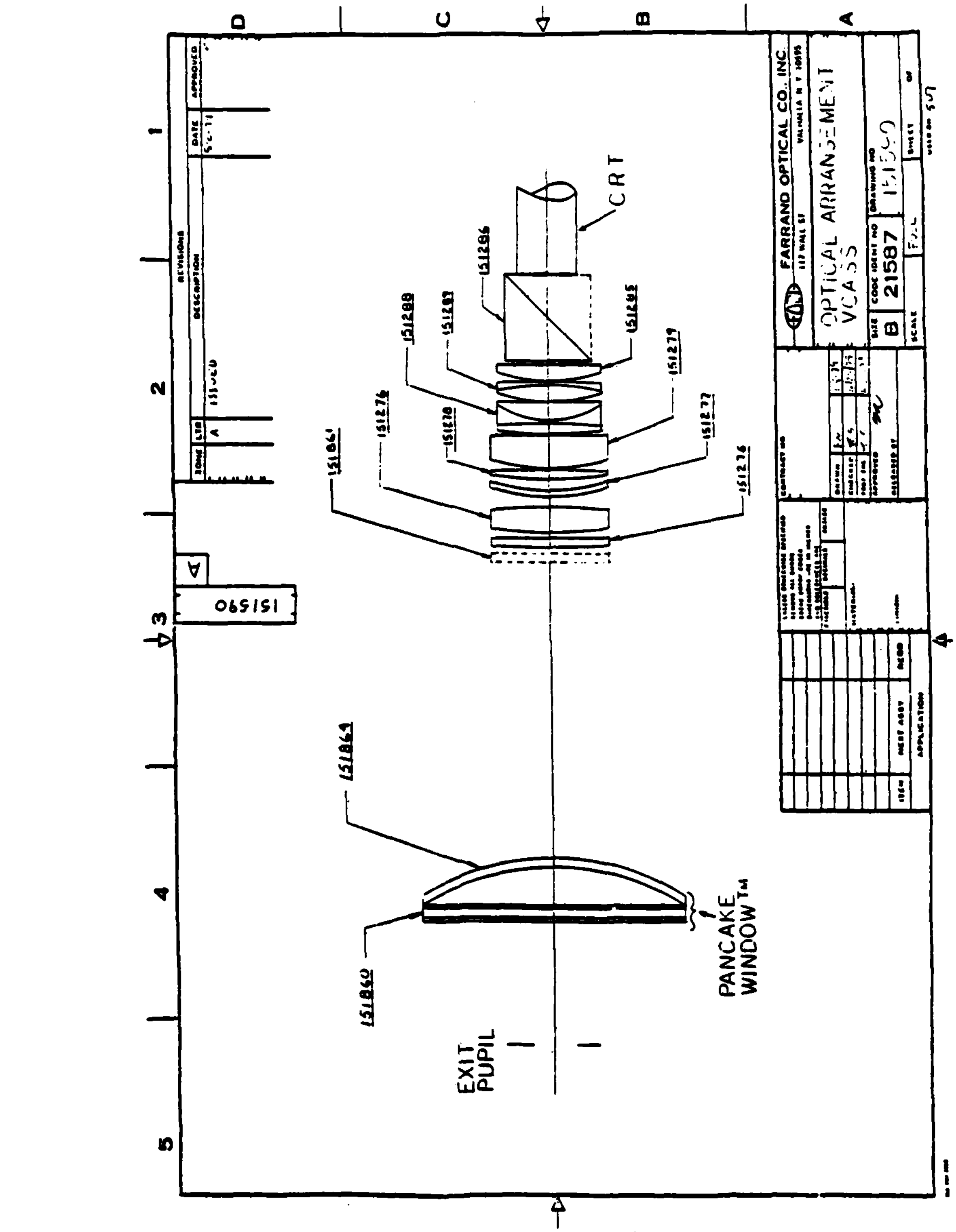
DOUBLET ASSY RELAY LENS SYSTEM
VCASS

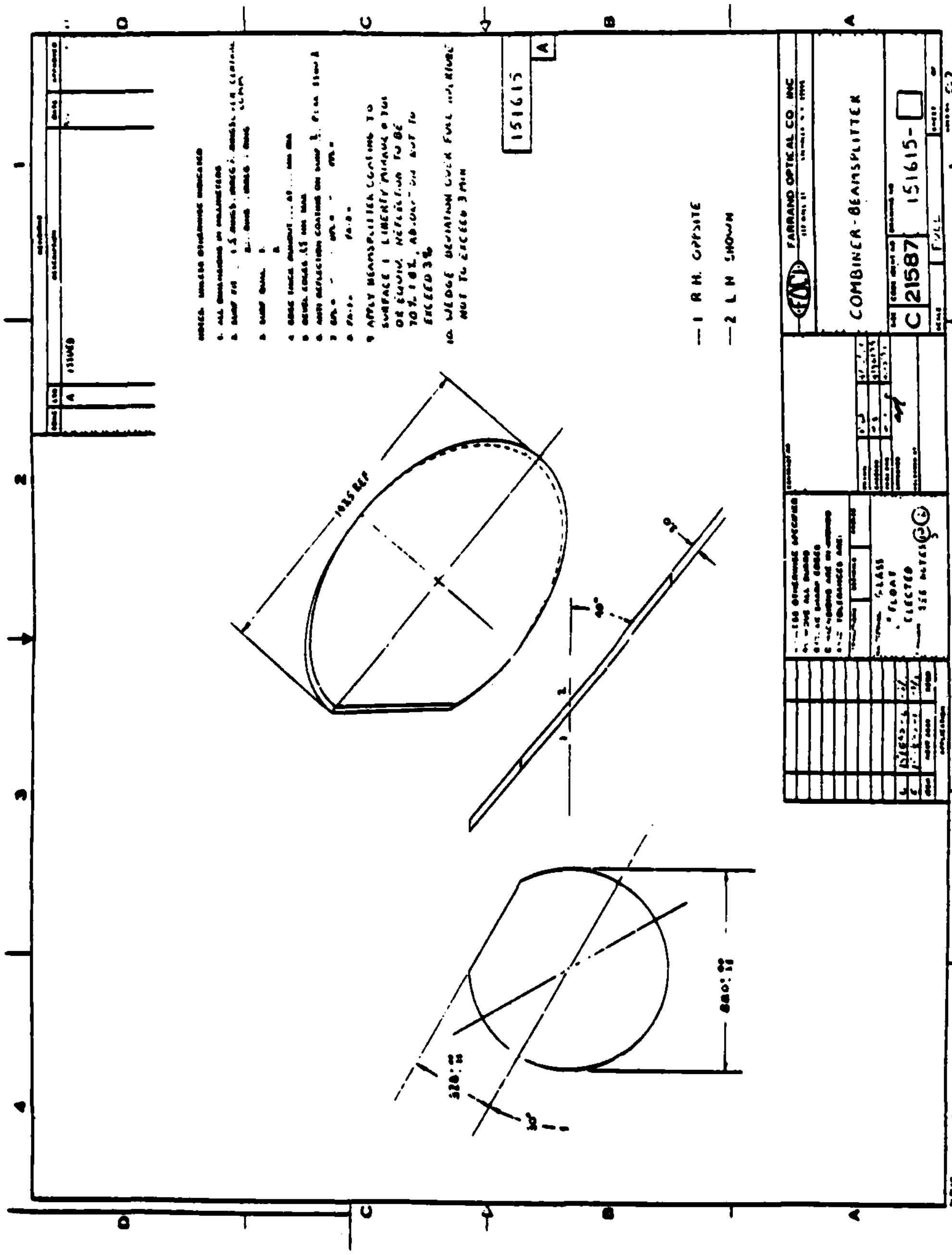
SIZE	CODE IDENT NO	DRAWING NO
B	21587	151289

DRAWN PW
CHECKED WS
APPROVED

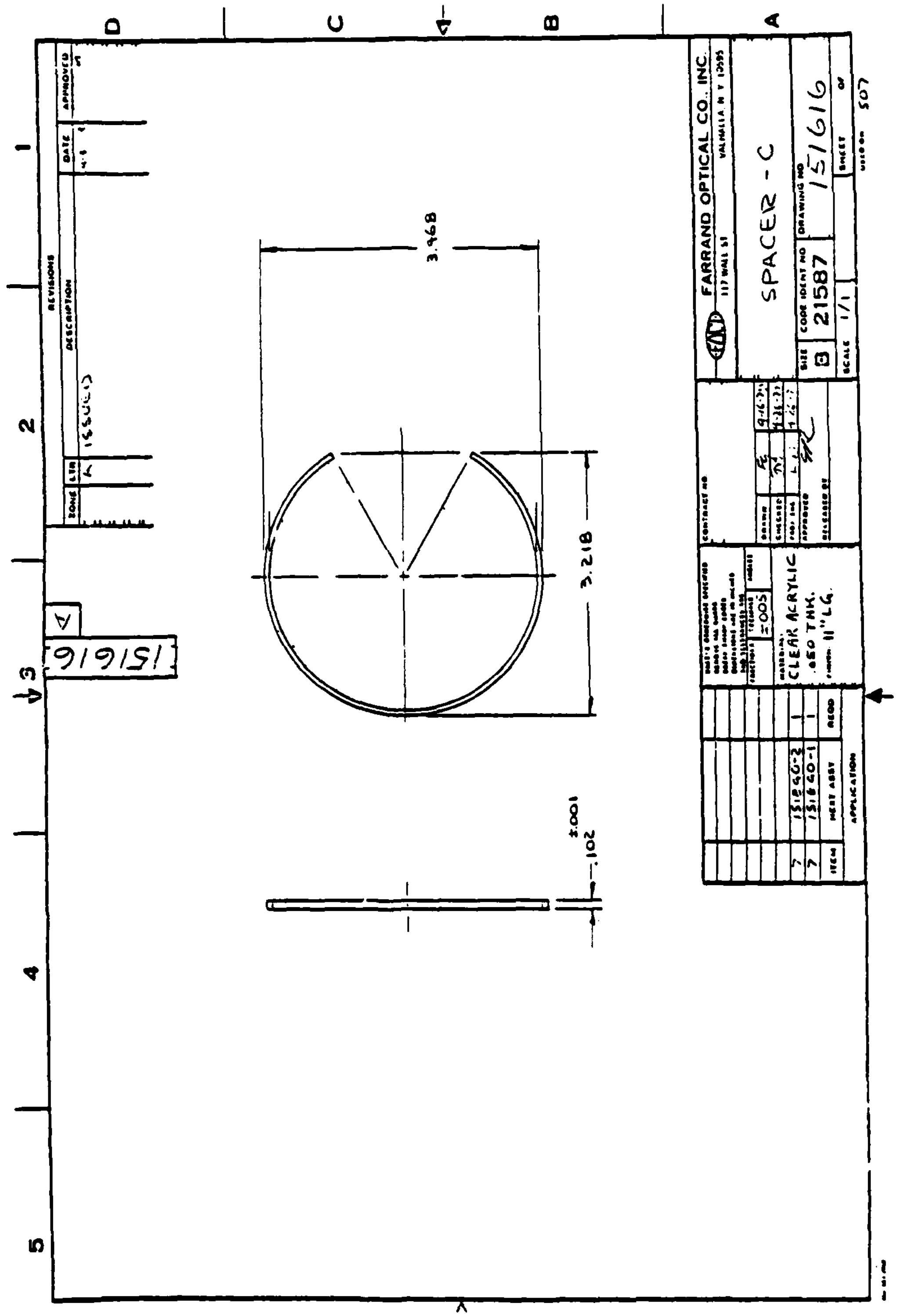
SCALE — SHEET — OF —
USED ON 507

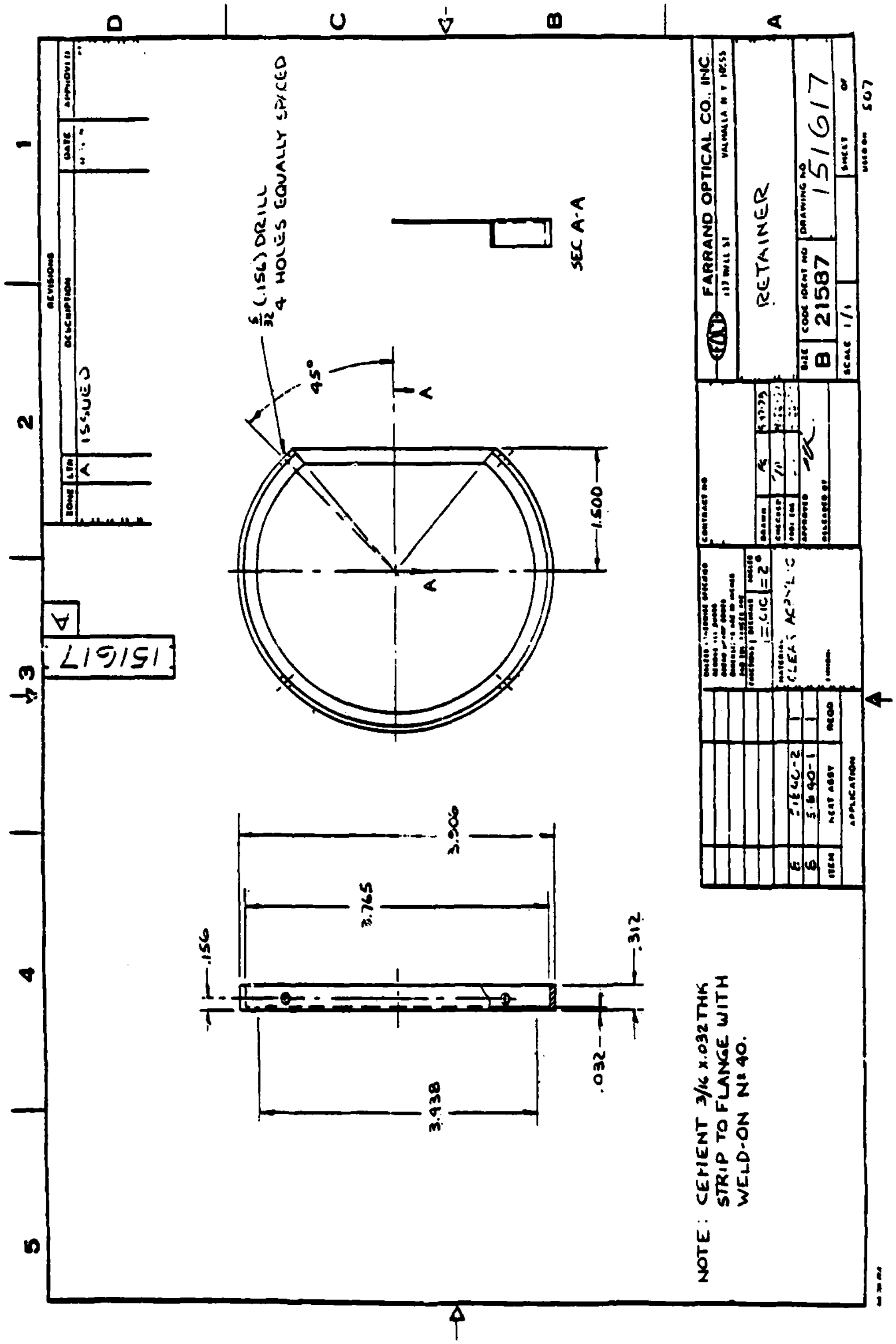
ITEM | NEXT ASSY | REQD
APPLICATION

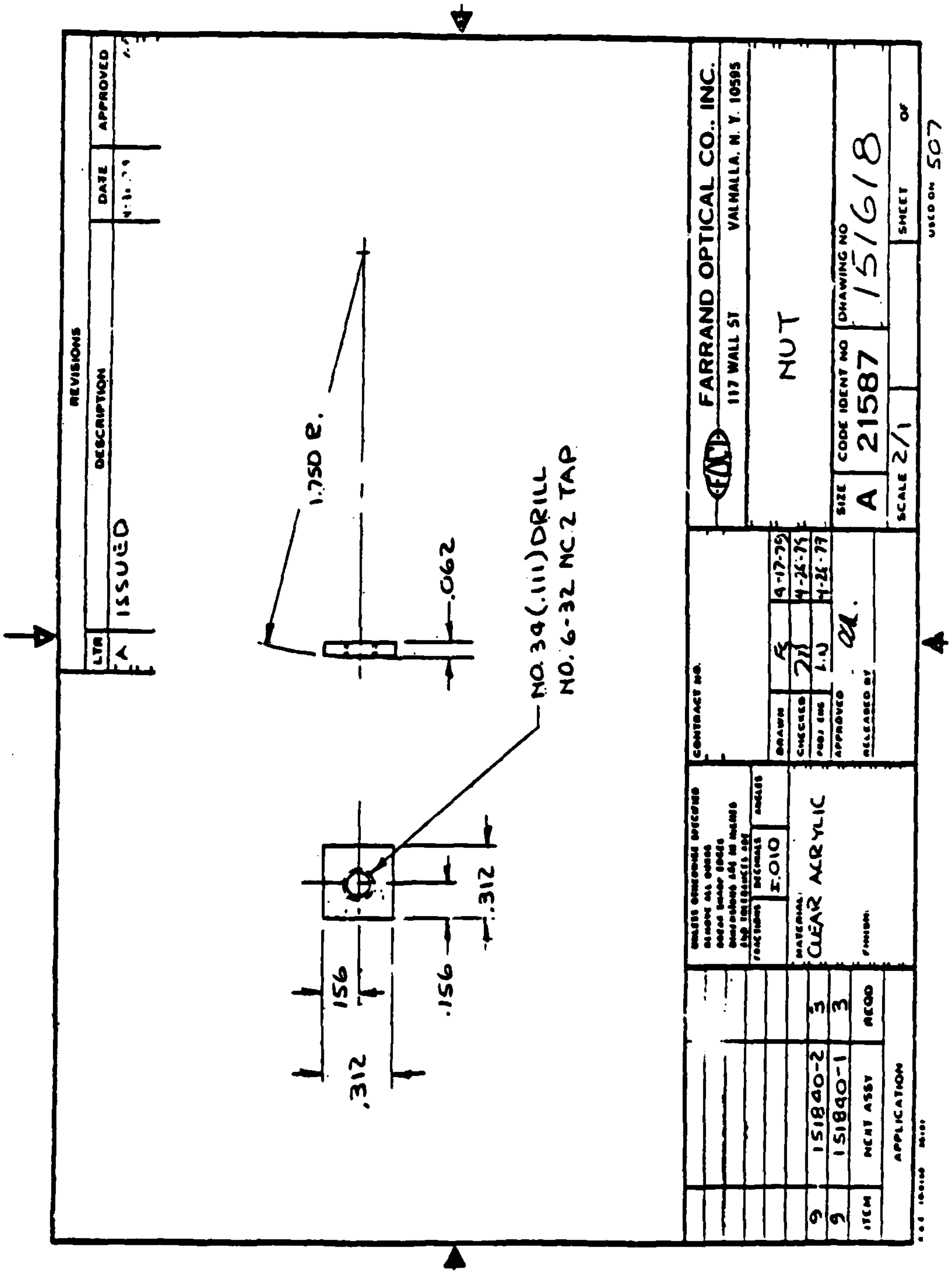

FARRAND OPTICAL CO., INC.
OPTICAL ARRANGEMENT
VCASS
21587
151590
CRT
151286
151288
151287
151285
151279
151276
151278
151277
151861
151864
151860
PANCAKE
WINDOW™
EXIT
PUPIL



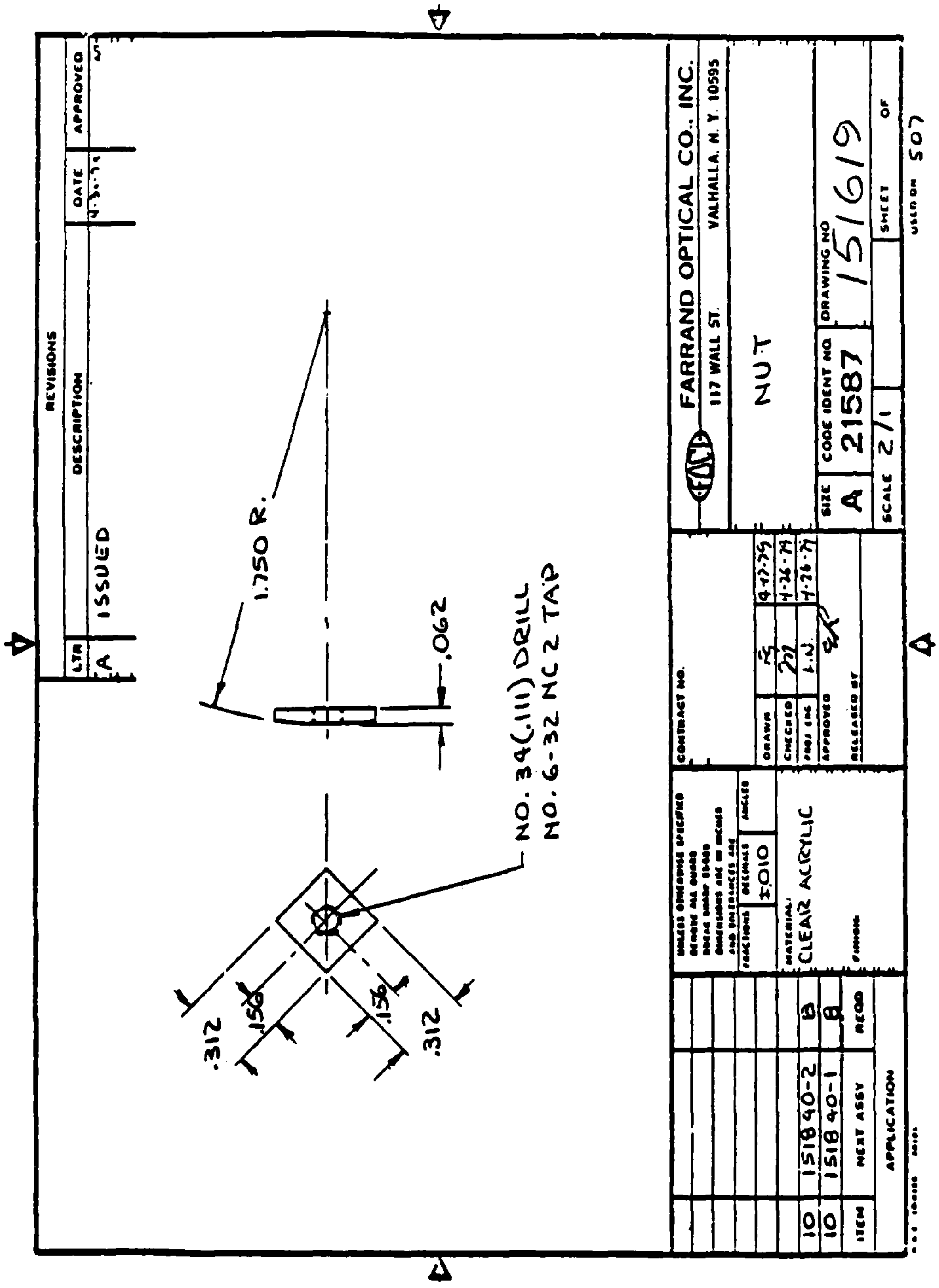
COMBINER-BEAMSPLITTER
FARRAND OPTICAL CO. INC
C 21587
151615-
151615
1 R.H. OPPOSITE
2 L.H. SHOWN
ISSUED

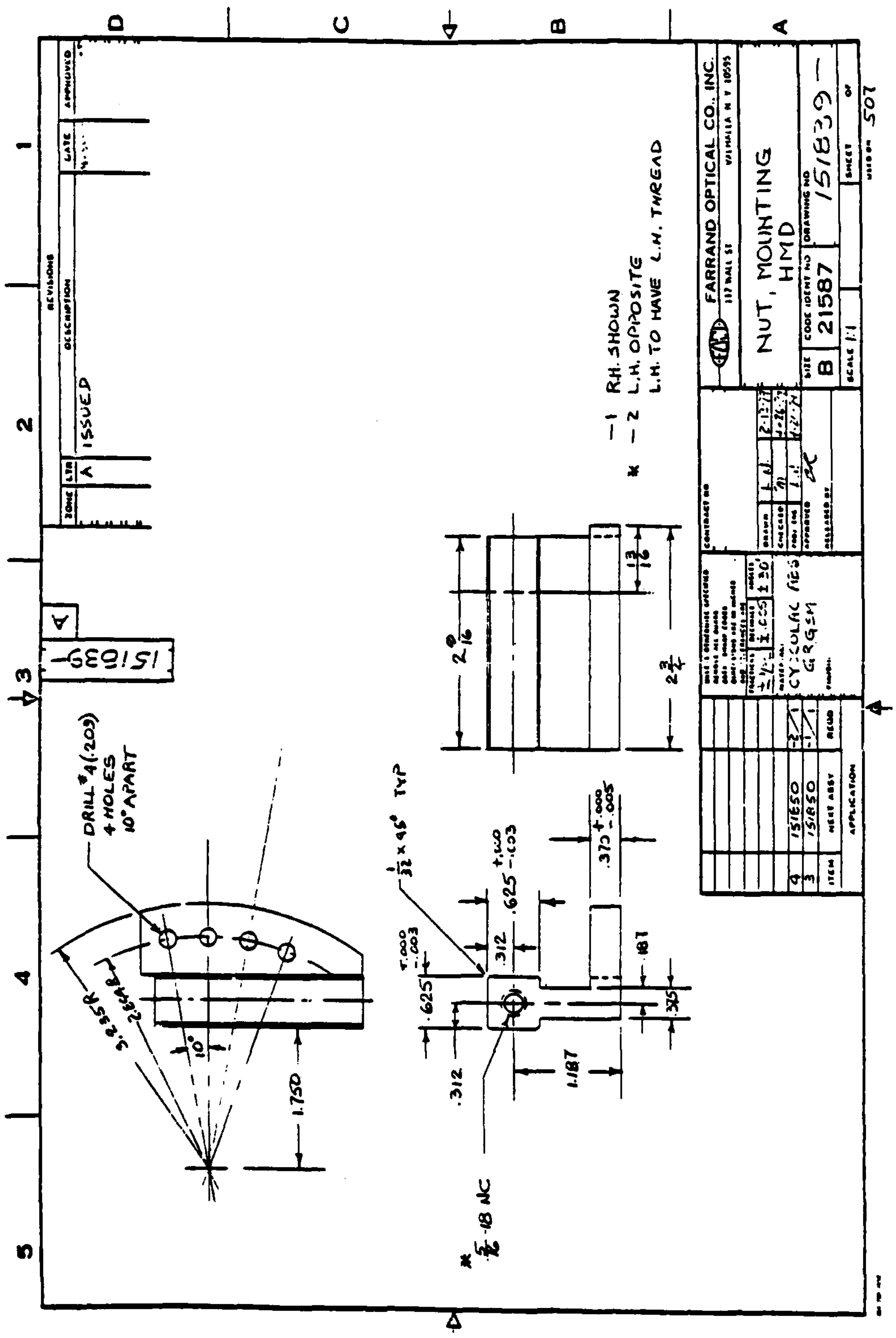

REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
ISSUED
151616
A
3.968
3.218
±.001
.102
CLEAR ACRYLIC
.060 THK.
11" LG.
±.005
151640-2
151640-1
ITEM
NEXT ASSY
APPLICATION
REQD
DRAWN
CHECKED
APPROVED
RELEASED BY
CONTRACT NO
FARRAND OPTICAL CO. INC.
117 WALL ST
VALHALLA N.Y. 10595
SPACER - C
SIZE
B
CODE IDENT NO
21587
DRAWING NO
151616
SCALE 1/1
SHEET
D
C
B
A
1
2
3
4
5

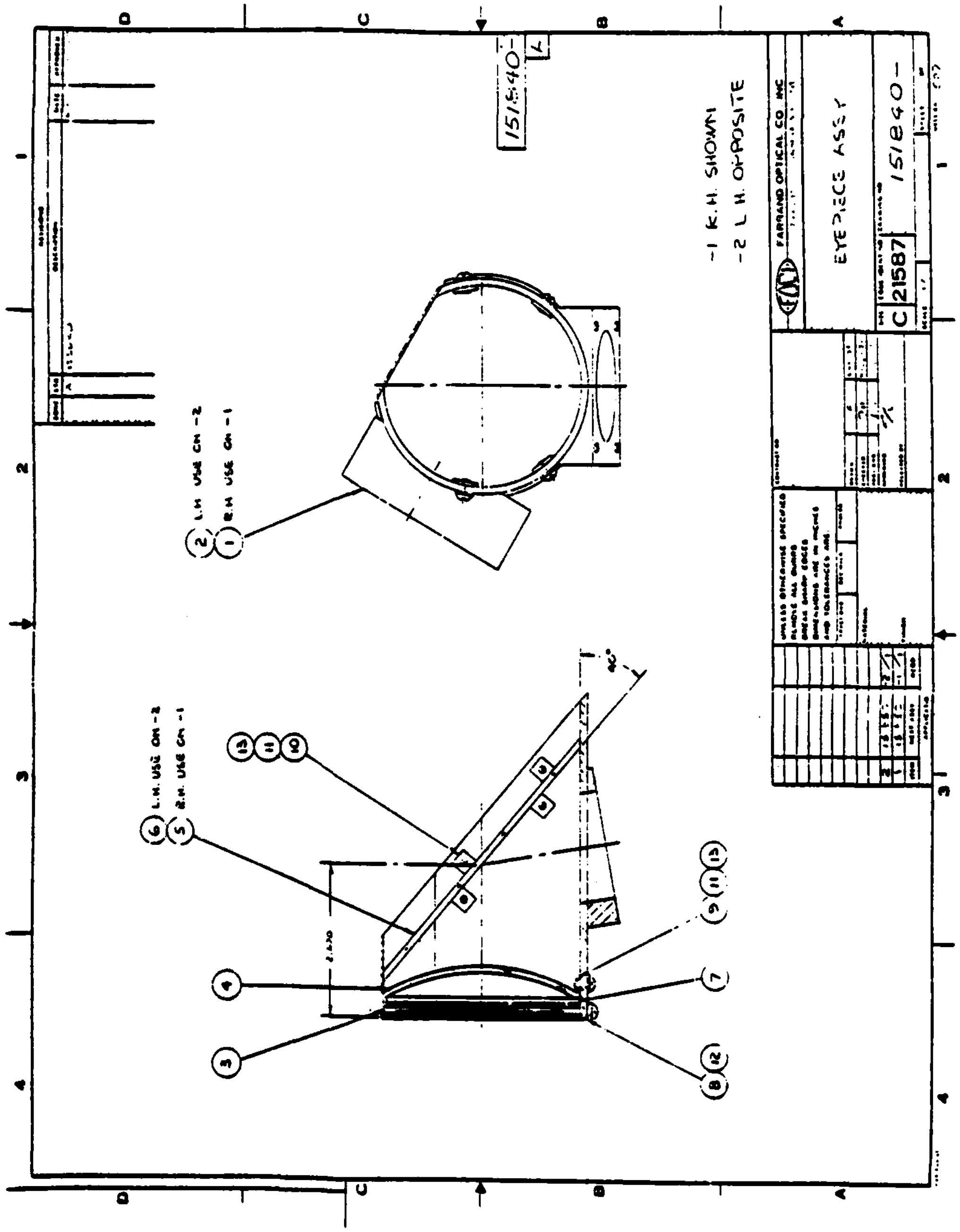

FARRAND OPTICAL CO., INC.
RETAINER
B
21587
151617
SCALE 1/1
REVISIONS
ISSUED
A
SEC A-A
5/32 (.156) DRILL
4 HOLES EQUALLY SPACED
45°
1.500
3.906
3.765
3.938
.156
.312
.032
NOTE: CEMENT 3/16 x .032 THK
STRIP TO FLANGE WITH
WELD-ON No 40.



REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
1.750 R.
.062
NO. 39 (.111) DRILL
NO. 6-32 NC 2 TAP
.312
.156
.156
.312
FARRAND OPTICAL CO., INC.
117 WALL ST
VALHALLA, N. Y. 10595
NUT
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151618
SCALE 2/1
SHEET
OF
USED ON 507
CONTRACT NO.
DRAWN
CHECKED
PROJ ENG
APPROVED
RELEASED BY
MATERIAL:
CLEAR ACRYLIC
FINISH:
±.010
151840-2
151840-1
3
3
ITEM
NEXT ASSY
REQD
APPLICATION


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
1.750 R.
.062
NO. 34(.111) DRILL
NO. 6-32 NC 2 TAP
.312
.156
.156
.312
FARRAND OPTICAL CO., INC.
117 WALL ST.
VALHALLA, N. Y. 10595
NUT
SIZE
A
CODE IDENT NO.
21587
DRAWING NO
151619
SCALE
2/1
SHEET
OF
CONTRACT NO.
DRAWN
CHECKED
APPROVED
RELEASED BY
FRACTIONS
DECIMALS
ANGLES
±.010
MATERIAL:
CLEAR ACRYLIC
FINISH:
10
151840-2
B
10
151840-1
B
ITEM
NEXT ASSY
REQD
APPLICATION


FARRAND OPTICAL CO., INC.
NUT, MOUNTING
HMD
21587
151839
REVISIONS
ISSUED
-1 R.H. SHOWN
* -2 L.H. OPPOSITE
L.H. TO HAVE L.H. THREAD
DRILL #4(.209)
4 HOLES
10° APART
1.750
1.187
.312
.625
SCALE 1:1


-1 R.H. SHOWN
-2 L.H. OPPOSITE
FARRAND OPTICAL CO. INC
EYEPIECE ASSY
C 21587
151840-
L.H. USE ON -2
R.H. USE ON -1

PARTS LIST

FARRAND OPTICAL CO., INC.

117 WALL ST VALHALLA N.Y. 10595

PL 151840- REV A

SHEET OF

PROJ 507

CODE IDENT 21587

LIST TITLE: EYEPIECE ASSY -1 R.H. -2 L.H.

	ITEM NO.	SIZE	PART NUMBER	REV	DESCRIPTION	-1	-2
	1	C	151841-1		EYEPIECE HOUSING ASSY R.H.	1	—
	2	C	151841-2		EYEPIECE HOUSING ASSY L.H.	—	1
	3	C	151660		BIREFRINGENT ASSY	1	1
	4	3	151664		SPHERICAL BEAMSPLITTER	1	1
	5	B	151615-1		COMBINER R.H.	1	—
	6	B	151615-2		COMBINER L.H.	—	1
	7	B	151616		SPACER - C	1	1
	8	E	151617		RETAINER	1	1
	9	A	151618		NUT	3	3
	10	A	151619		NUT	8	8
	11		COML		NYLON FLAT WASHER NO.6 SEWOO6O33	11	11
	12		COML		NYLON SLOTTED RD HD SCREW 6-32 X 3/16 LG	4	4
	13		COML		NYLON SLOTTED RD HD SCREW 6-32 X 1/4 LG	11	11

REVISION A

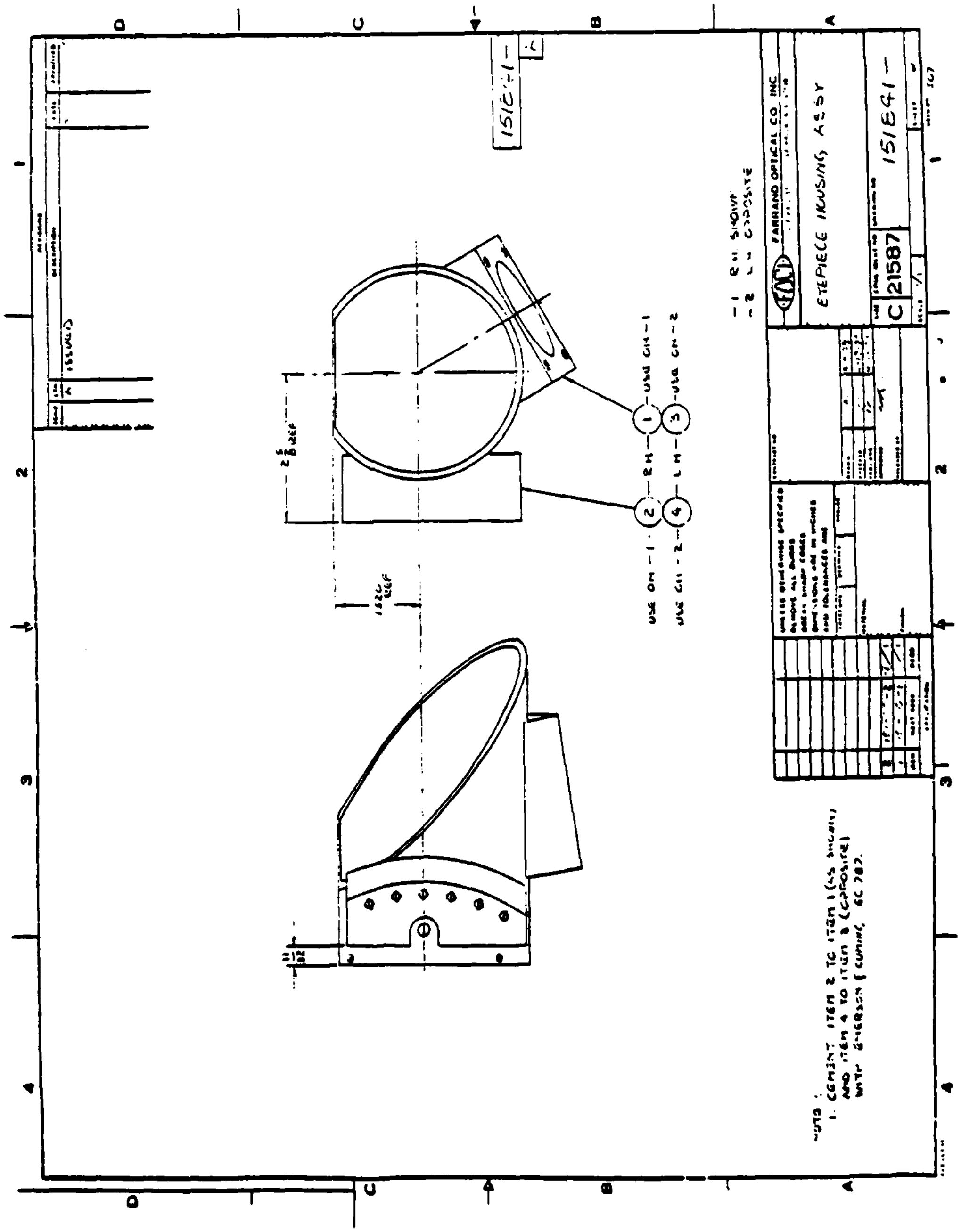
ASSY DRAWING NO. 151840-

SIZE C

PL 151840-

SHEET OF

USED ON 507


EYEPIECE HOUSING ASSY
FARRAND OPTICAL CO INC
C 21587
151E41-
-1 RH SHOWN
-2 LH OPPOSITE
USE ON -1
USE ON -2
NOTES:
1. CEMENT ITEM 2 TO ITEM 1 (AS SHOWN) AND ITEM 4 TO ITEM 3 (OPPOSITE) WITH EMERSON & CUMING, EC 787.

PARTS LIST

FARRAND OPTICAL CO., INC.
117 WALL ST VALHALLA N.Y. 10595

LIST TITLE	EYEPIECE HOUSING ASSY	PL151841 —	REV A
		SHEET OF	
		PROJ 507	PR
		CODE IDENT	21587

ITEM	SIZE	PART NUMBER	DESCRIPTION	-1	-2
1	C	151842 -	HOUSING R.H	1	—
2	C	151843 -1	SHOE R.H	1	—
3	C	151842 -2	HOUSING L.H	—	1
4	C	151843 -2	SHOE L.H	—	1

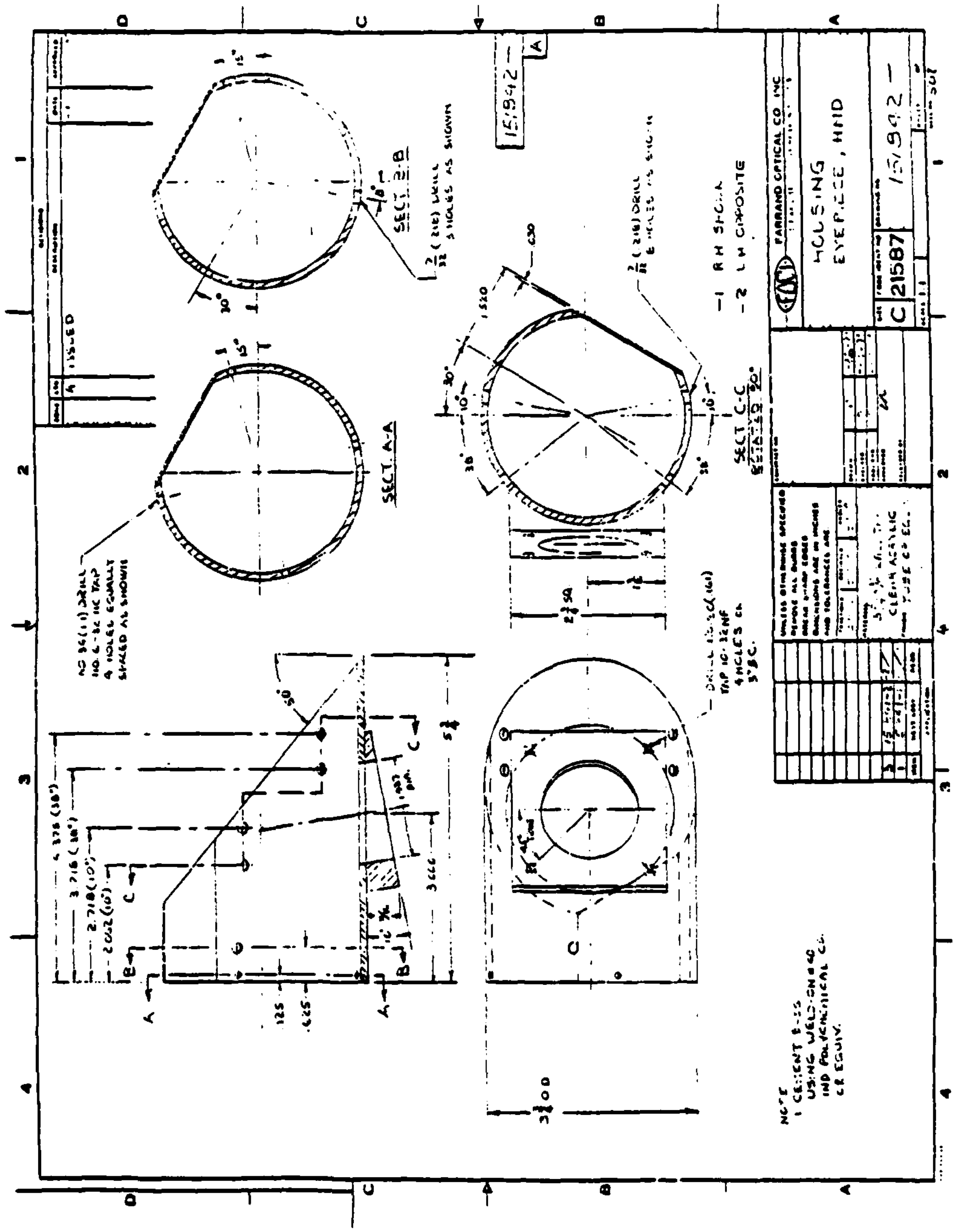
ASSY DRAWING NO 151841 —

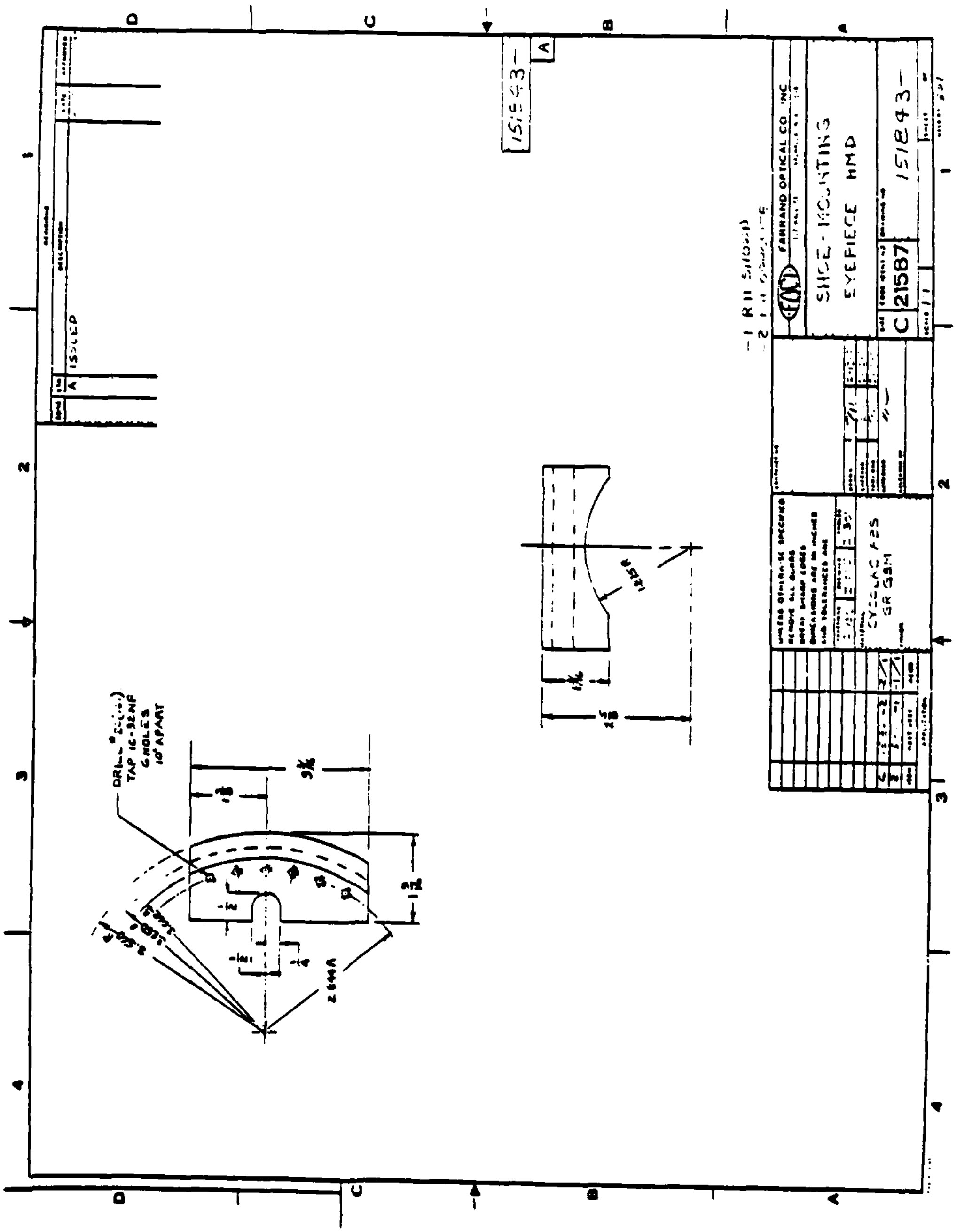
SIZE C REV A

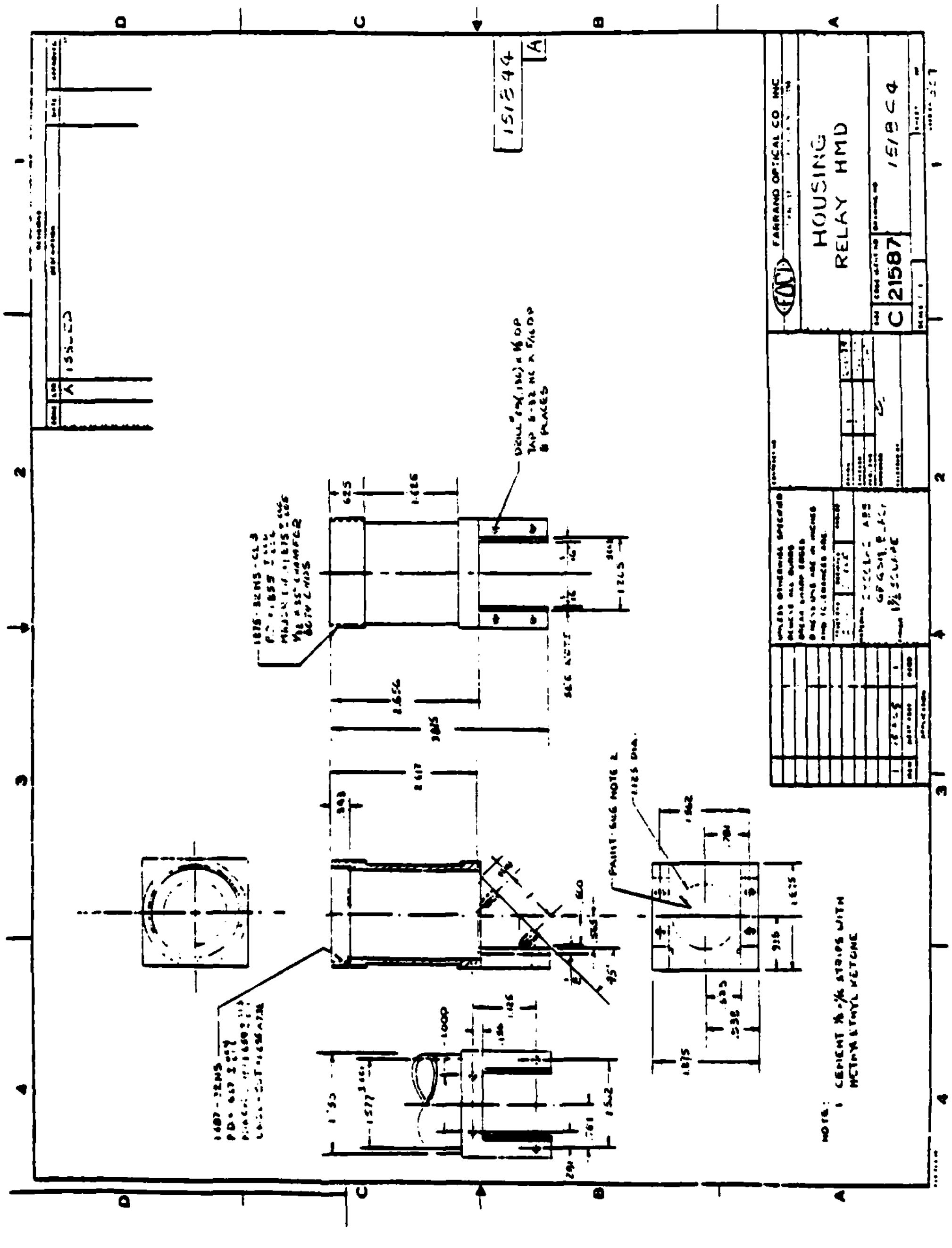
PL151841 —

SHEET OF

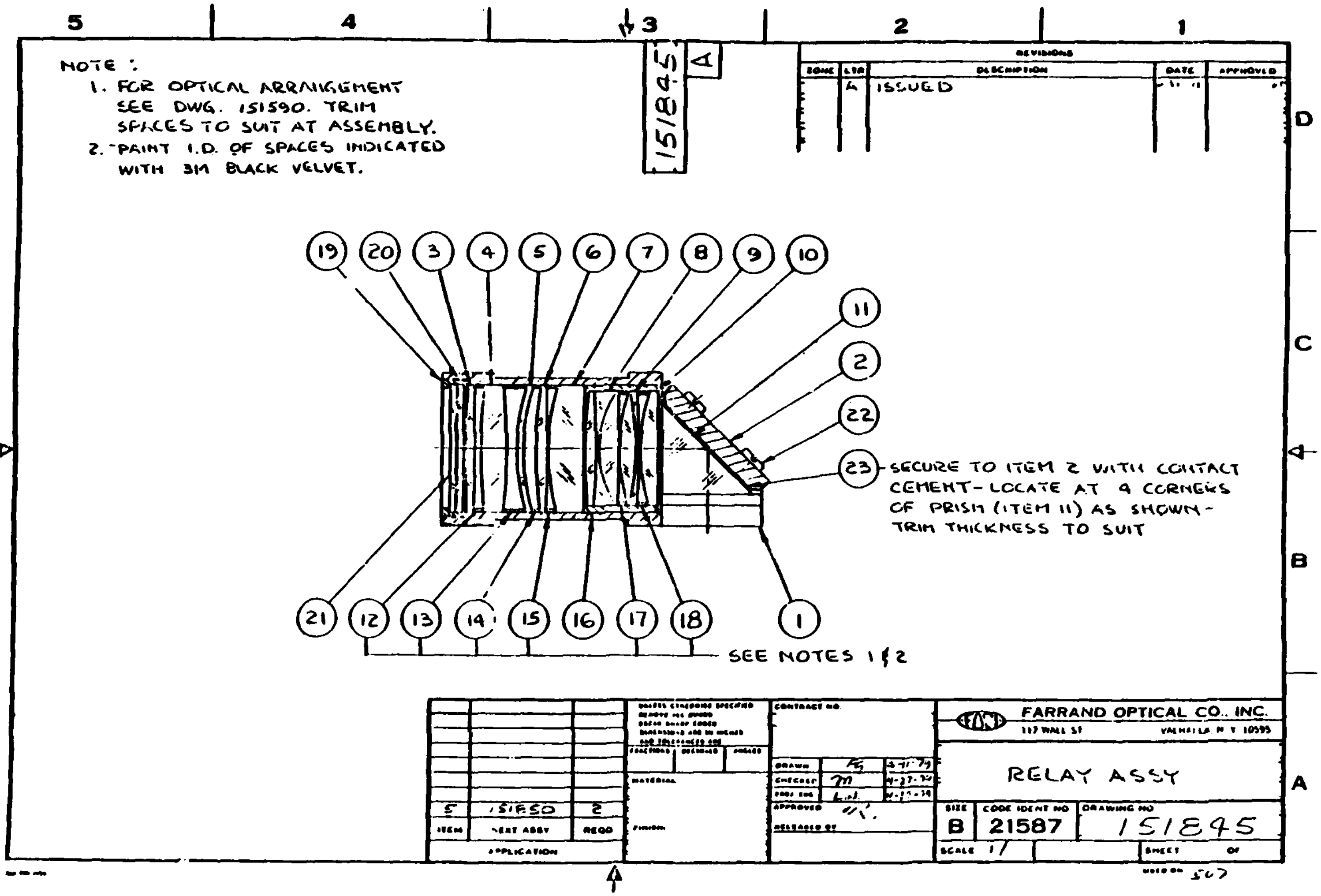
USED ON 507


FARRAND OPTICAL CO INC
HOUSING
EYEPIECE, HMD
C 21587
SECT A-A
SECT C-C


FARRAND OPTICAL CO. INC
SHOE - MOUNTING
EYEPIECE HMD
C
21587
151843-
ISSUED
CYCOLAC ABS
GR GSM
DRILL TAP 10-32NF 6 HOLES 10° APART



HOUSING
RELAY HMD
FARRAND OPTICAL CO. INC.
C 21587
151844
PAINT SEE NOTE 2
.125 DIA.
SEE NOTE


NOTE :
1. FOR OPTICAL ARRANGEMENT SEE DWG. 151590. TRIM SPACES TO SUIT AT ASSEMBLY.
2. PAINT I.D. OF SPACES INDICATED WITH 3M BLACK VELVET.
151845
A
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
19
20
3
4
5
6
7
8
9
10
11
2
22
23
SECURE TO ITEM 2 WITH CONTACT CEMENT-LOCATE AT 4 CORNERS OF PRISM (ITEM 11) AS SHOWN-TRIM THICKNESS TO SUIT
21
12
13
14
15
16
17
18
1
SEE NOTES 1 & 2
5
151850
2
ITEM
NEXT ASSY
REQD
APPLICATION
MATERIAL
FINISH
CONTRACT NO
DRAWN
CHECKED
APPROVED
RELEASED BY
FARRAND OPTICAL CO., INC.
117 WALL ST
VALHALLA N Y 10595
RELAY ASSY
SIZE
CODE IDENT NO
DRAWING NO
B
21587
151845
SCALE
1/1
SHEET
OF
USED ON 507

PARTS LIST

FARRAND OPTICAL CO., INC.

117 WALL ST VALHALLA N Y 10595

LIST TITLE RELAY ASSY

PL 151845 REV A

SHEET OF

PROJ 507 PR

CODE IDENT 21587

	Item	Rev	Part Number		Description	Qty
	1	C	151844		HOUSING	1
	2	A	151846		RETAINER	1
	3	A	151275		LENS NO. 1	1
	4	A	151276		LENS NO. 2	1
	5	A	151277		LENS NO. 3	1
	6	A	151278		LENS NO. 4	1
	7	A	151279		LENS NO. 5	1
	8	B	151288		TRIPLET	1
	9	B	151289		DOUBLET	1
	10	A	151285		LENS NO. 11	1
	11	A	151286		PRISM	1
	12	B	151855-1		SPACER A	1
	13	B	151855-2		SPACER B	1
	14	B	151855-3		SPACER C	1
	15	B	151855-4		SPACER D	1
	16	A	151856		CELL-LENS	1
	17	B	151857-1		SPACER E	1
	18	B	151857-2		SPACER F	1
	19	-	151859		RETAINER	1
	20	A	151858		RETAINER-LENS	1
	21	A	151861		LINEAR POLARIZER	1
	22		COML		NYLON SLOTTED PAN HD SCREW 8-32 x 7/16	4
	23		COML		CORKPRENE 1/8 SQ x 1/32 THK	4
	REF	B	151590		OPTICAL ARRANGEMENT	—

REVISION A

LIST OF 5

APPROVED 11-72

ASSY DRAWING NO 151845

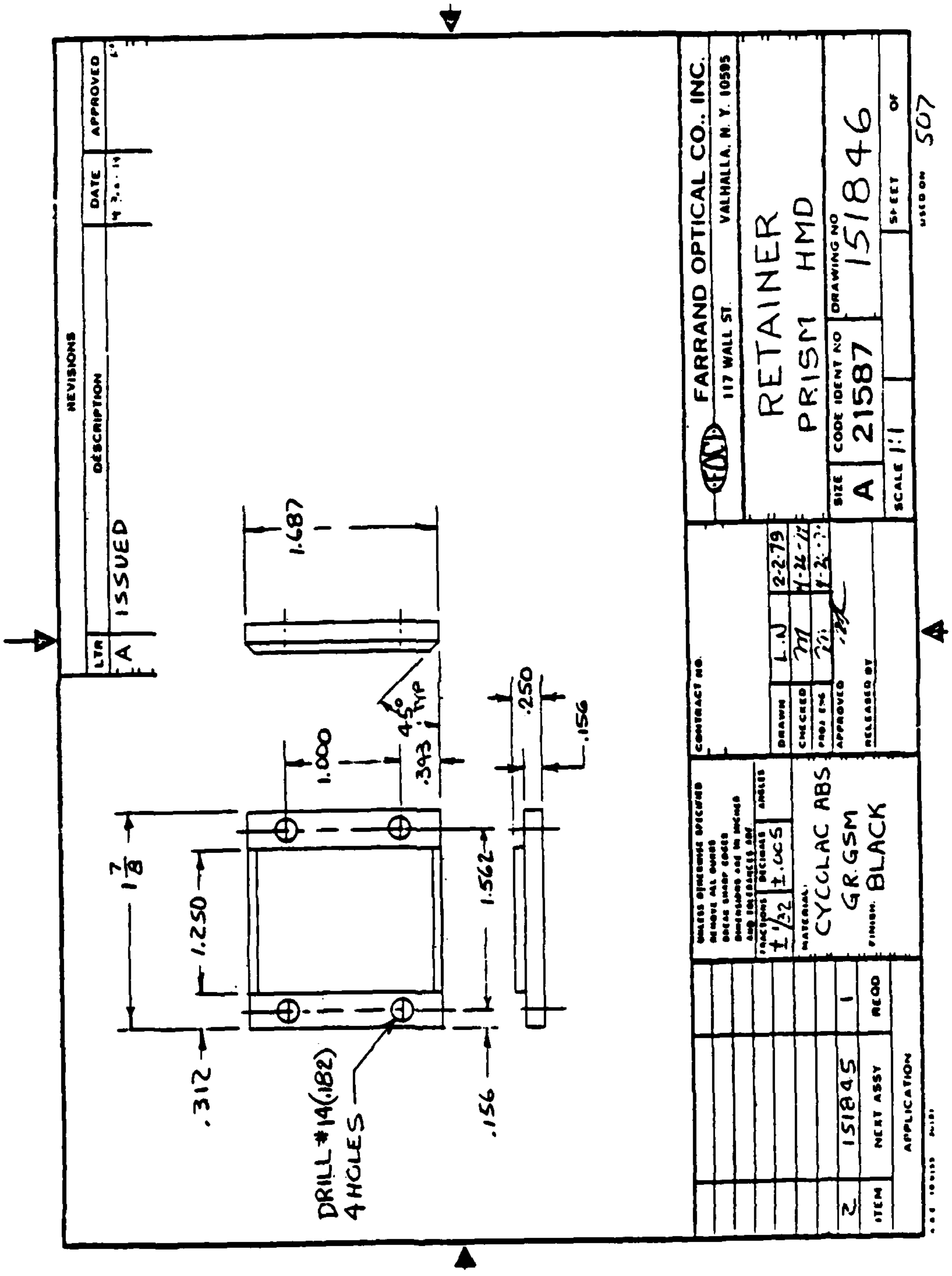
SIZE D

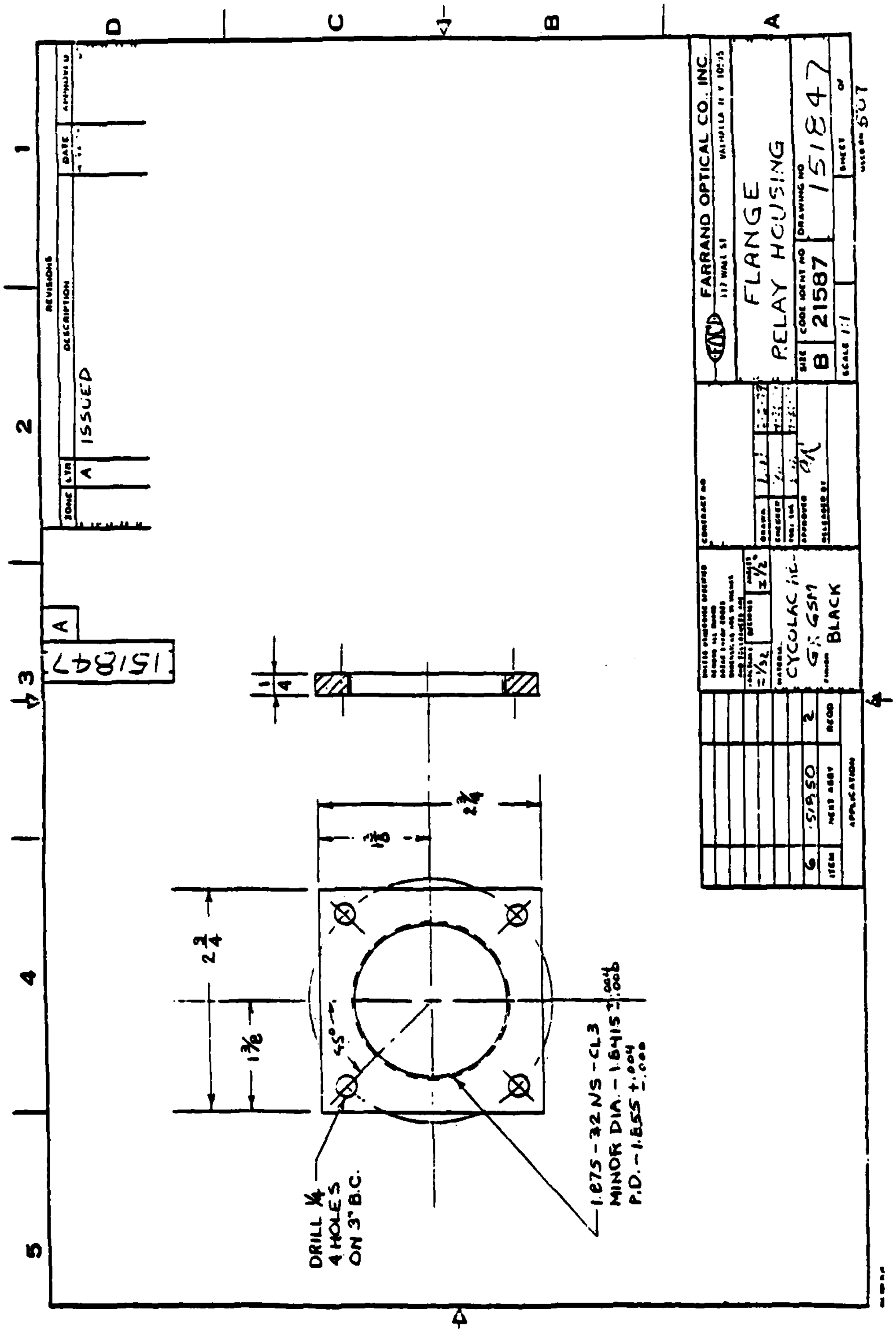
REL A

PL 151845

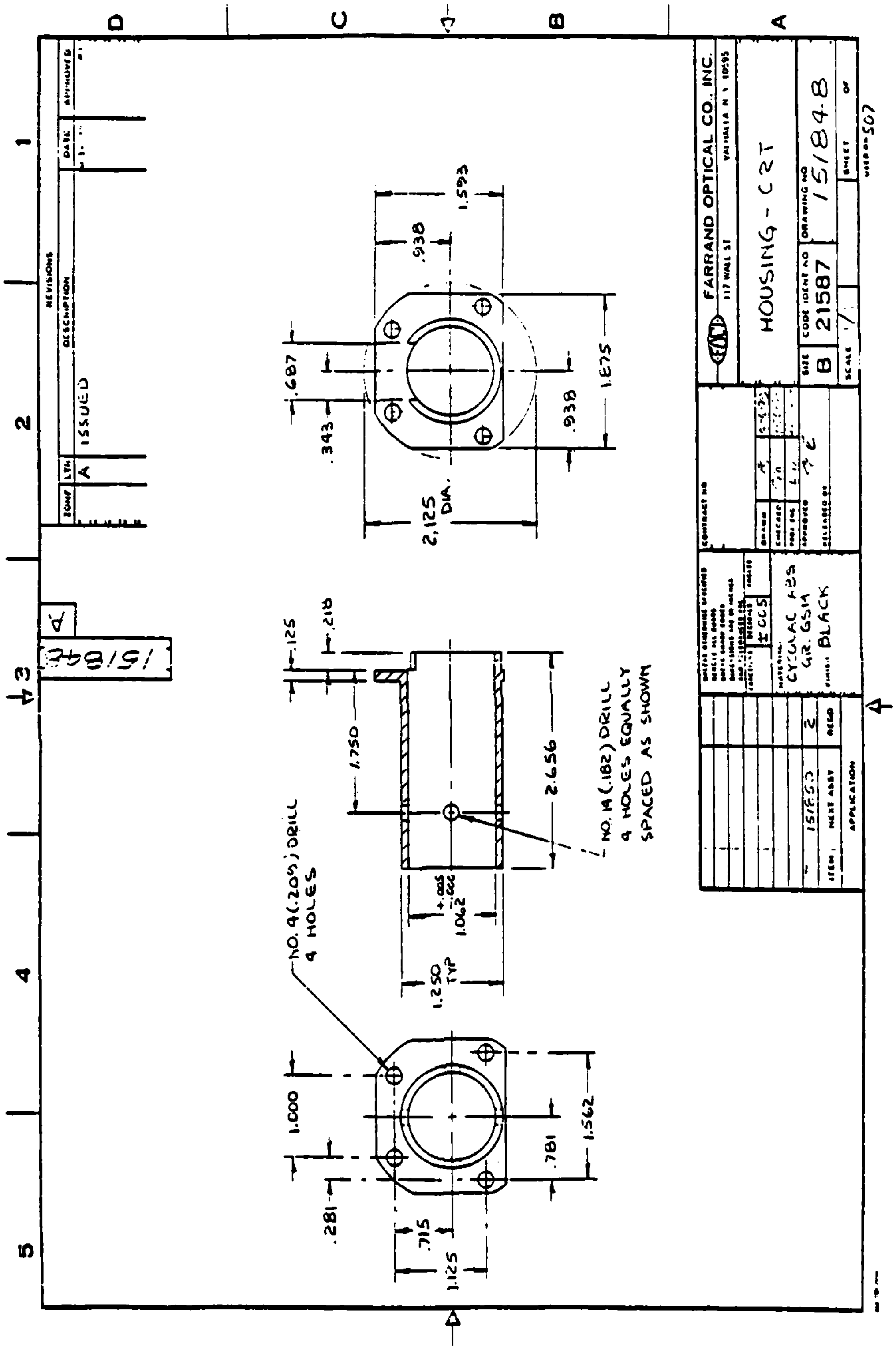
SHEET OF

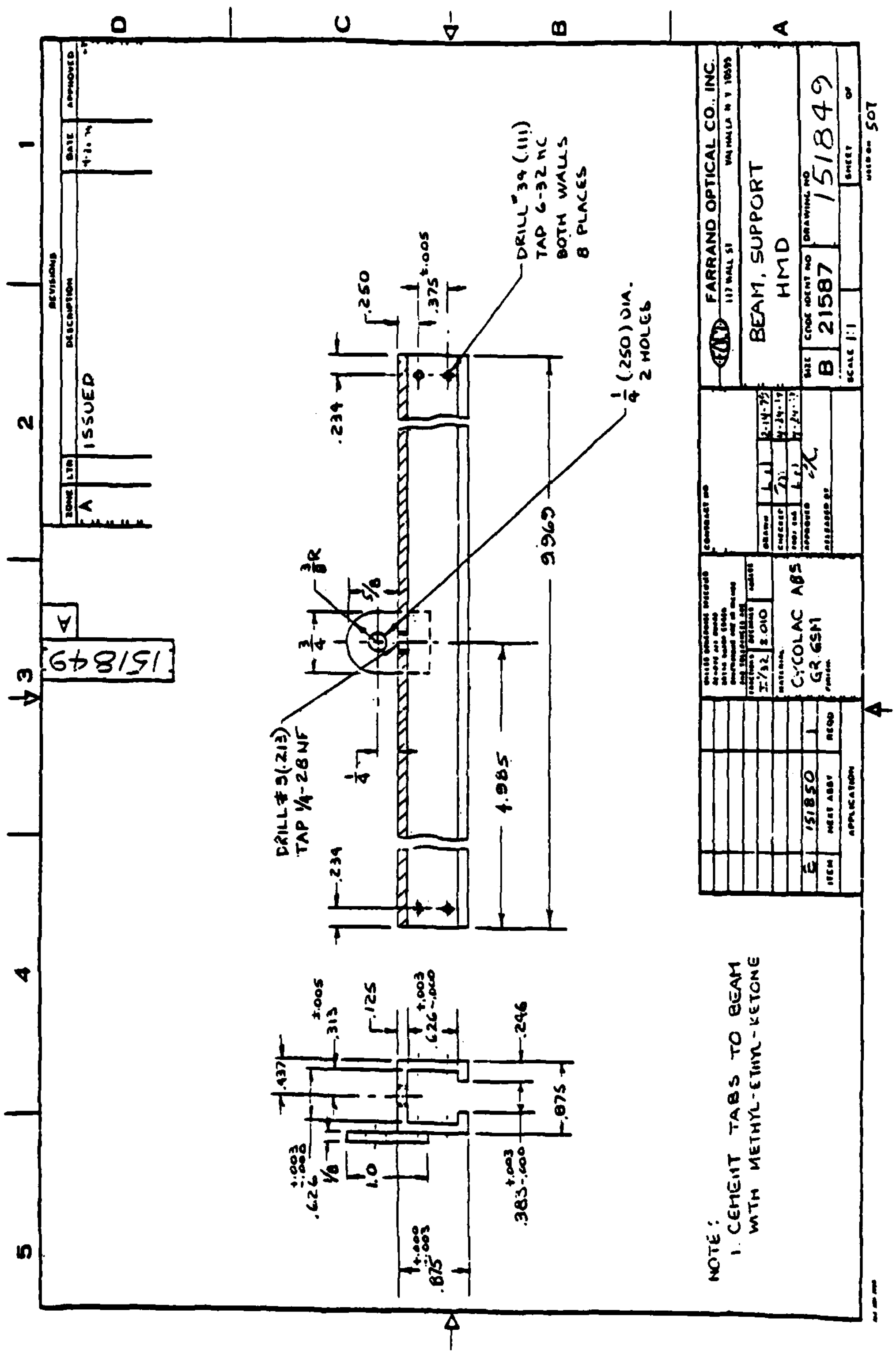
USED ON 507


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
1 7/8
1.250
.312
1.562
.156
DRILL #14(.182)
4 HOLES
1.000
.393
45° TYP
1.687
.250
.156
FARRAND OPTICAL CO., INC.
117 WALL ST.
VALHALLA, N. Y. 10595
RETAINER
PRISM HMD
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151846
SCALE 1:1
SHEET
OF
USED ON
507
CONTRACT NO.
DRAWN
L.J
2-2-79
CHECKED
APPROVED
RELEASED BY
MATERIAL
CYCOLAC ABS
GR.GSM
FINISH
BLACK
FRACTIONS
± 1/32
DECIMALS
±.005
ANGLES
2
151845
1
ITEM
NEXT ASSY
REQD
APPLICATION



FARRAND OPTICAL CO. INC.
FLANGE
RELAY HOUSING
REVISIONS
DESCRIPTION
ISSUED
B
21587
151847
SCALE 1:1
BLACK
DRILL 1/4
4 HOLES
ON 3" B.C.
1.875 - 32 NS - CL3
MINOR DIA. - 1.8415
P.D. - 1.855


FARRAND OPTICAL CO. INC.
HOUSING - CRT
CODE IDENT NO 21587
DRAWING NO 151848
B
REVISIONS
ISSUED
NO. 4 (.209) DRILL
4 HOLES
NO. 14 (.182) DRILL
4 HOLES EQUALLY
SPACED AS SHOWN
2.125 DIA.
1.875
1.593
.938
.687
.343
1.750
2.656
1.250 TYP
1.062
1.000
1.562
.781
.281
.715
1.125
.125
.218
CYCOLAC ABS
GR. GSM
BLACK
NEXT ASSY
APPLICATION



FARRAND OPTICAL CO. INC.
117 WALL ST VALHALLA N Y 10595
BEAM, SUPPORT
HMD
SIZE B
CODE IDENT NO 21587
DRAWING NO 151849
SCALE 1:1
SHEET OF
REVISIONS
ZONE LTR DESCRIPTION DATE APPROVED
A ISSUED
151849
A
DRILL #39 (.111)
TAP 6-32 NC
BOTH WALLS
8 PLACES
1/4 (.250) DIA.
2 HOLES
DRILL #3 (.213)
TAP 1/4-28 NF
3/8 R
5/16
3/4
1/4
.250
.375 ±.005
.234
9.969
4.985
.437
.313 ±.005
.125
.626 +.003 -.000
.246
.875
.626 +.003 -.000
1/8
1.0
.383 +.003 -.000
.875 +.000 -.003
NOTE:
1. CEMENT TABS TO BEAM
WITH METHYL-ETHYL-KETONE
CYCOLAC ABS
GR GSM
±1/32
±.010
DRAWN
CHECKED
APPROVED
RELEASED BY
151850 1
ITEM NEXT ASSY REQD
APPLICATION

PARTS LIST

FARRAND OPTICAL CO., INC.

117 WALL ST VALHALLA N.Y. 10595

LIST TITLE: HELMET MOUNTED DISPLAY ASSY (CASS)

PL 151850 A

SHEET OF

PROJ 507 FR

CODE IDENT 21587

	Item	Size	Part Number		Description	Qty
	1	C	151640-1		EYEPIECE ASSY R.H.	1
	2	C	151640-2		EYEPIECE ASSY L.H.	1
	3	P	151839-1		NUT - MOUNTING R.H	1
	4	E	151839-2		NUT - MOUNTING L.H	1
	5	B	151845		RELAY ASSY	2
	6	B	151847		FLANGE - RELAY HOUSING	2
	7	B	151846		HOUSING - C.R.T.	2
	8	B	151849		BEAM	1
	9	A	151851		SCREW - ADJUST.	1
	10	A	151852		BUSHING	2
	11	A	151853		SCREW - DOG	1
	12	B	151854		BRACKET	2
	13		CFE		C.R.T. FERRANTI CR 3136	2
	14		COML		KNOB RB-201 RCGAY	1
	15		COML		NYLON SLOTTED PAN HD SCREW 6-32 X 3/16	8
	16		COML		NYLON SLOTTED PAN HD SCREW 6-32 X 7/16	8
	17		COML		NYLON SLOTTED PAN HD SCREW 10-32 X 1/2	12
	18		COML		NYLON SLOTTED PAN HD SCREW 1/4-20 X 1/2	2
	19		COML		NYLON SLOTTED RD HD SCREW 6-32 X 1/4	8
	20		COML		NYLON SLOTTED RD HD SCREW 1/4-20 X 3/8	2
	21		COML		NYLON SHOULDER WASHER MICRO PLASTICS 25WS2502	2
	22		COML		KNURLED NYLON THUMB SCREW MICRO PLASTICS 0252CC30T	2
	23		COML		NYLON CORD 1/8 DIA.	5 FT
	24		COML		NYLON LACING CORD	AR
	25	F	151874		HELMET - MODIFIED	1
	REF	B	151590		OPTICAL ARRANGEMENT	—
	SEE	B	151863		LENS DATA	

REVISION A

LIST BY R.

APPROVED N.K.

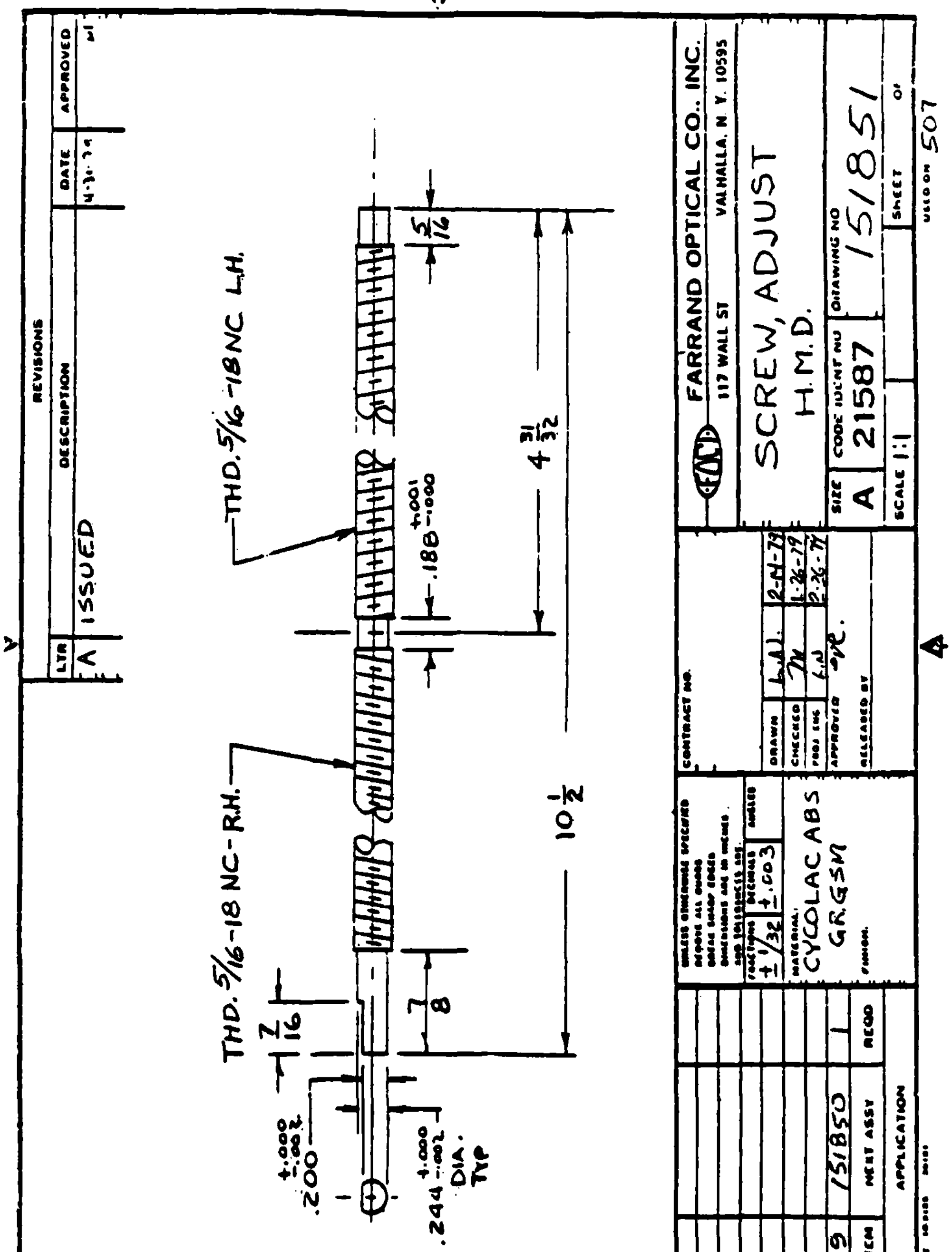
ASSY DRAWING NO 151850

SIZE F REV A

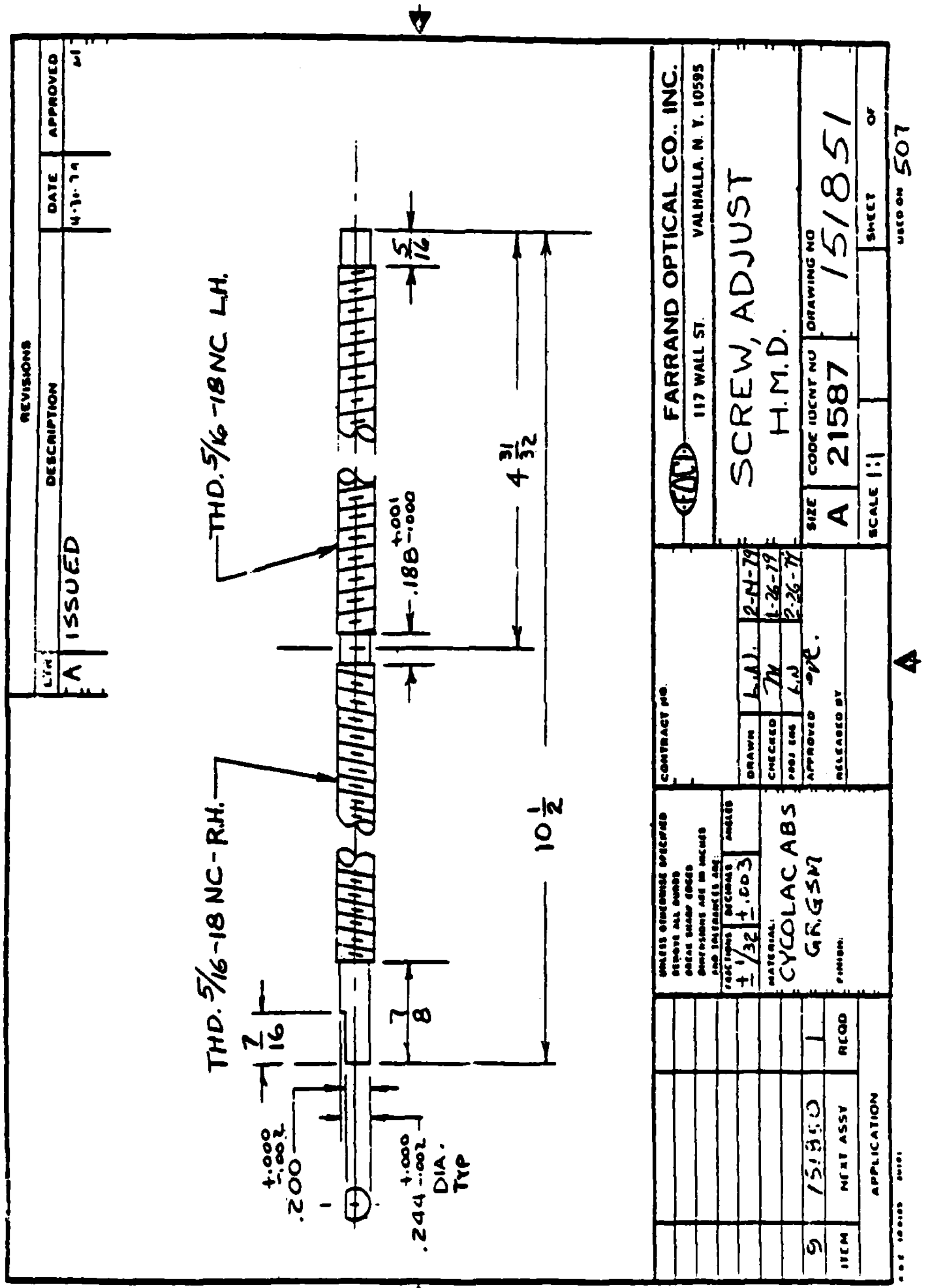
PL 151850

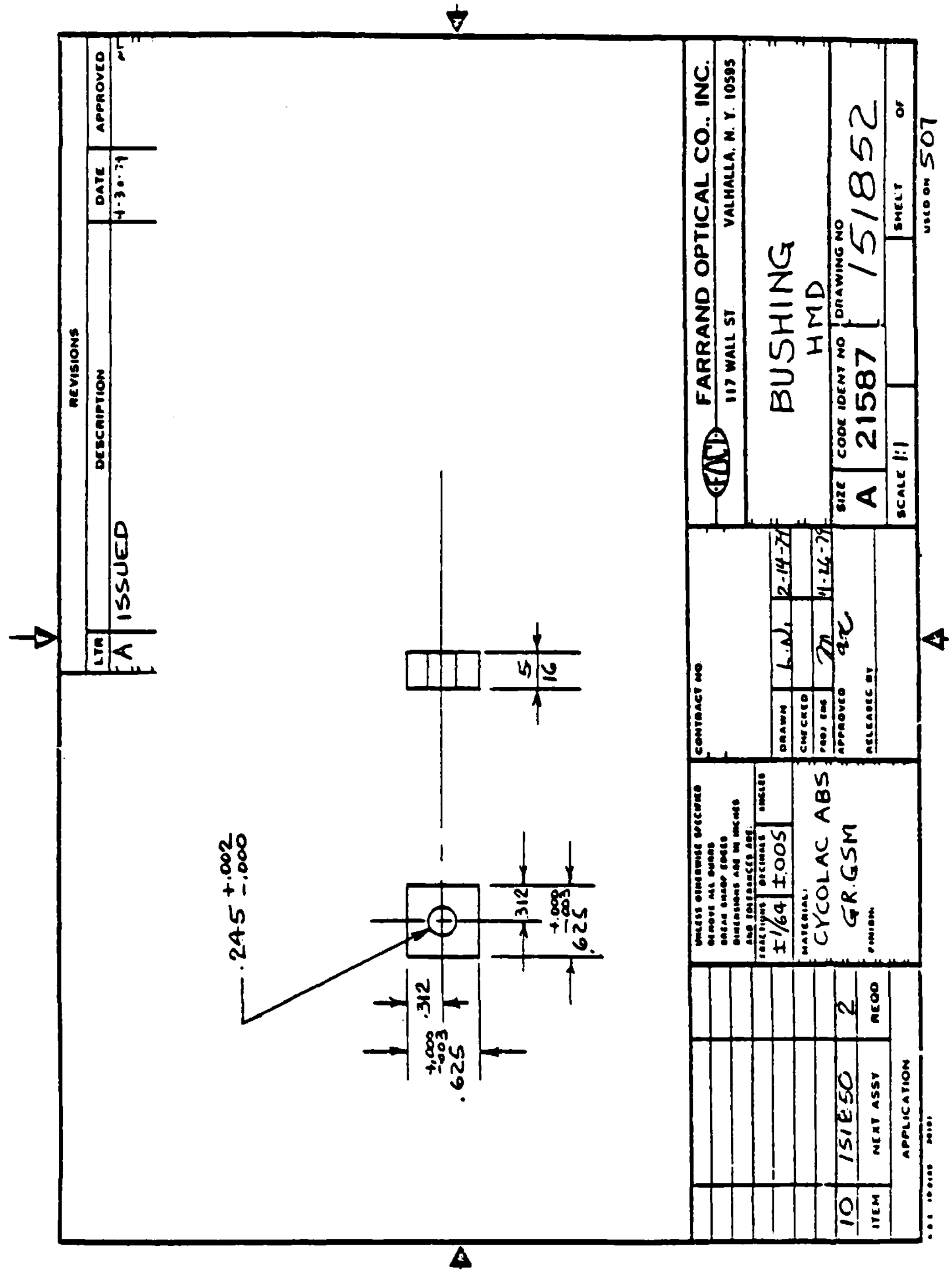
SHEET OF

USED ON 507

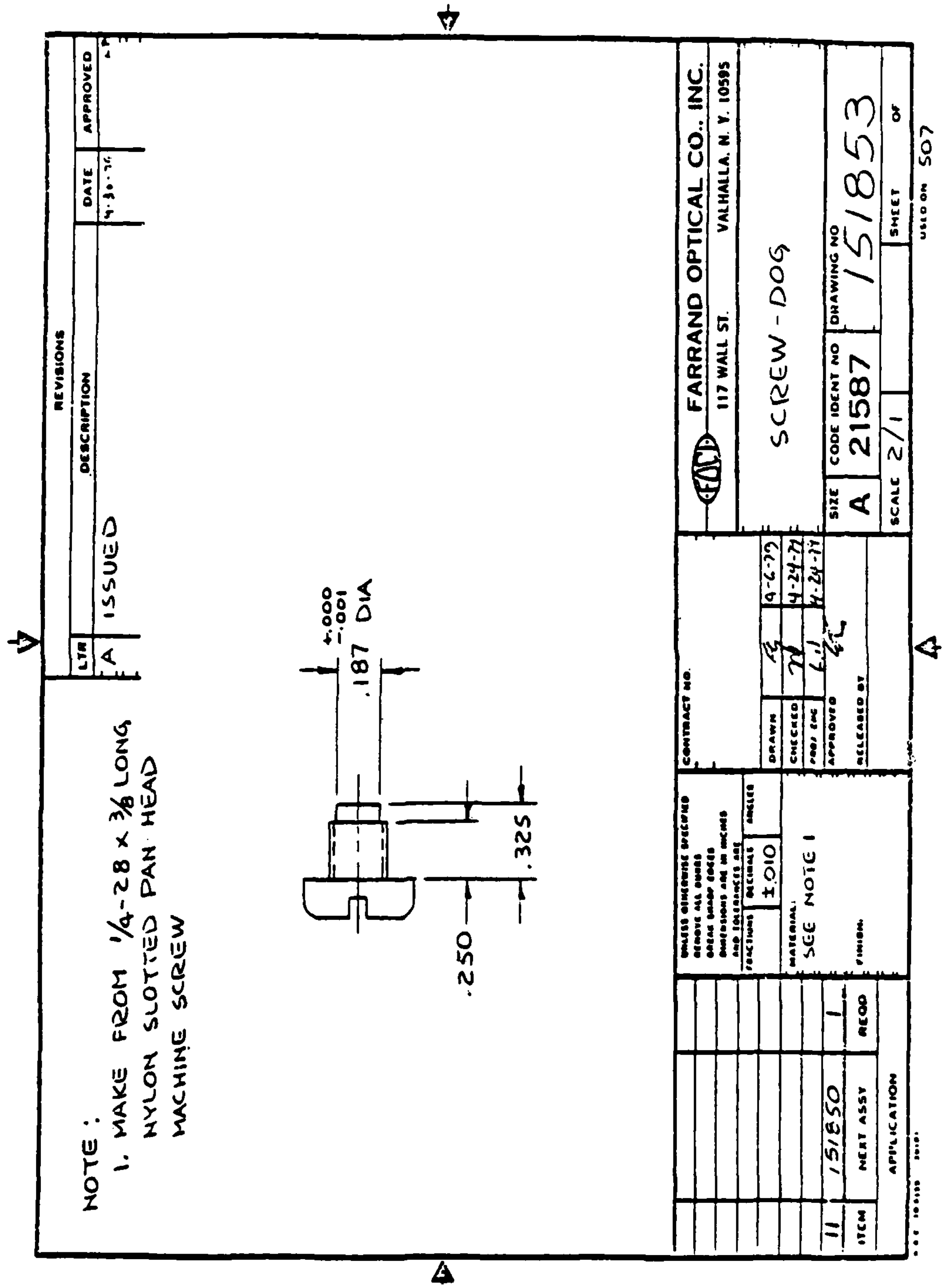


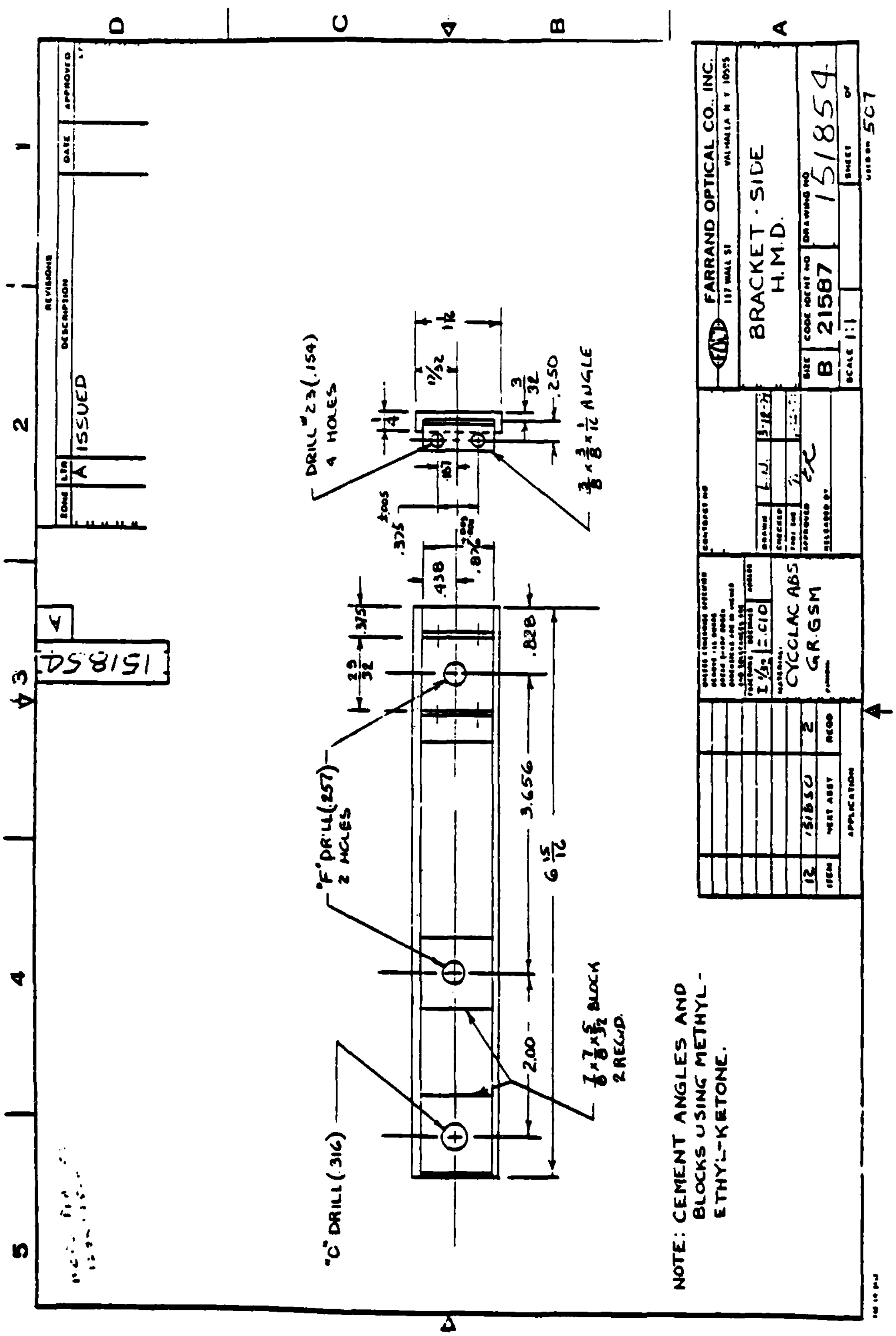
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
THD. 5/16-18 NC-R.H.
THD. 5/16-18NC L.H.
.200 +.000 -.002
.244 +.000 -.002 DIA. TYP
7/16
7/8
10 1/2
4 31/32
.188 +.001 -.000
5/16
FARRAND OPTICAL CO., INC.
117 WALL ST
VALHALLA, N. Y. 10595
SCREW, ADJUST
H.M.D.
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151851
SCALE 1:1
SHEET
507
CONTRACT NO.
DRAWN
CHECKED
APPROVED
RELEASED BY
2-14-79
2-26-79
MATERIAL:
CYCOLAC ABS
GRGSM
FINISH:
UNLESS OTHERWISE SPECIFIED
± 1/32
±.003
9
151850
1
ITEM
NEXT ASSY
REQD
APPLICATION


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
THD. 5/16-18NC L.H.
THD. 5/16-18 NC-R.H.
.188 +.001 -.000
4 31/32
10 1/2
5/16
7/16
7
8
.200 +.000 -.002
.244 +.000 -.002 DIA. TYP
FARRAND OPTICAL CO. INC.
117 WALL ST.
VALHALLA, N. Y. 10595
SCREW, ADJUST
H.M.D.
MATERIAL:
CYCOLAC ABS
CONTRACT NO
DRAWN
CHECKED
APPROVED
RELEASED BY
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151851
SCALE 1:1
SHEET
OF
USED ON 507
ITEM
NEXT ASSY
REQD
APPLICATION

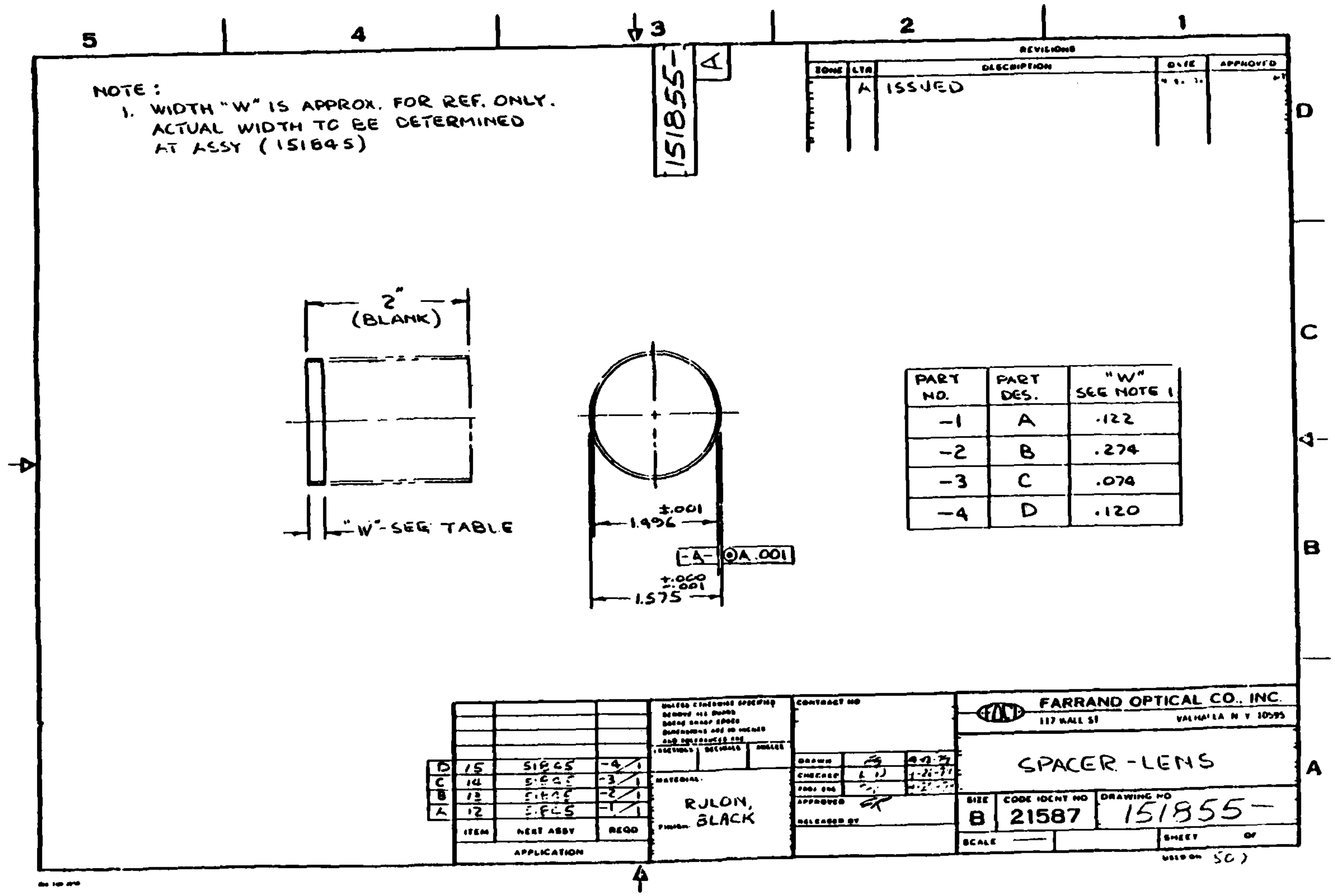


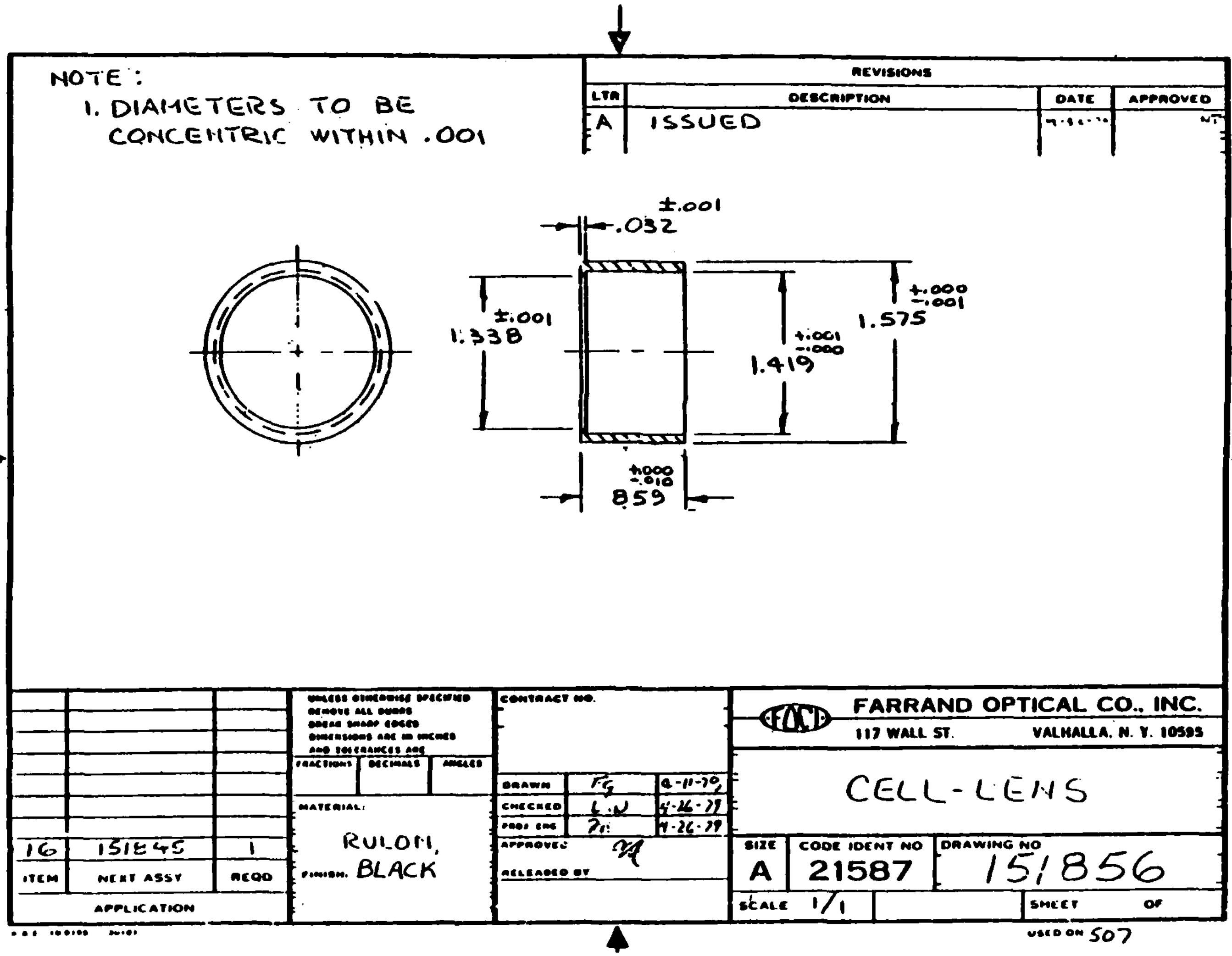
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
.245 +.002 -.000
.312
.625 +.000 -.003
5/16
FARRAND OPTICAL CO. INC.
117 WALL ST.
VALHALLA, N. Y. 10595
BUSHING
HMD
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151852
SCALE 1:1
SHEET
OF
USED ON 507
CONTRACT NO
DRAWN
CHECKED
APPROVED
RELEASED BY
MATERIAL:
CYCOLAC ABS
GR.GSM
FINISH:
±1/64
±.005
10
151850
2
ITEM
NEXT ASSY
REQD
APPLICATION

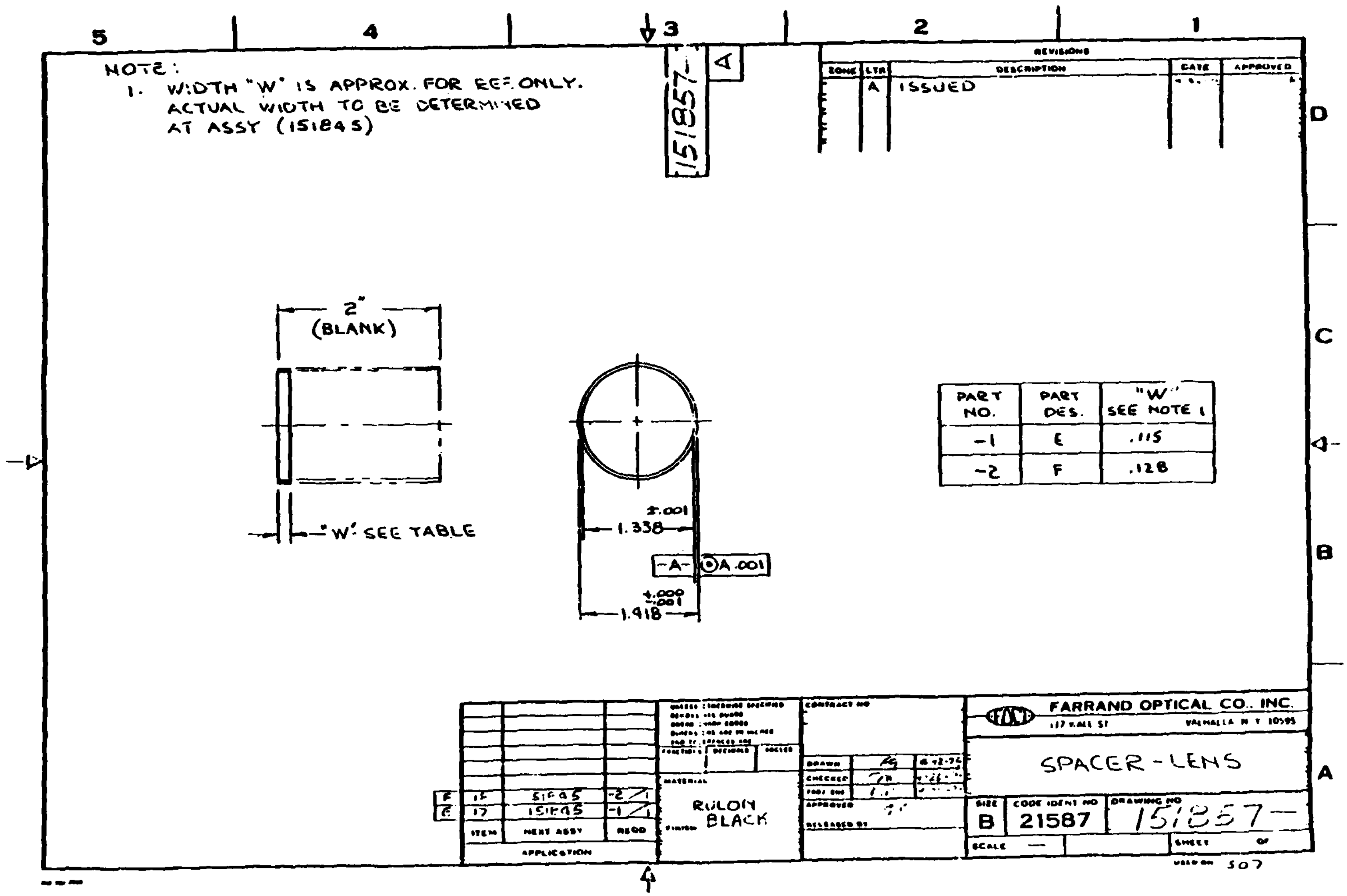

NOTE:
1. MAKE FROM 1/4-28 x 3/8 LONG NYLON SLOTTED PAN HEAD MACHINE SCREW
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
+.000
-.001
.187 DIA
.325
.250
FARRAND OPTICAL CO., INC.
117 WALL ST.
VALHALLA, N. Y. 10595
SCREW - DOG
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151853
SCALE 2/1
SHEET
USED ON 507
CONTRACT NO.
DRAWN
CHECKED
APPROVED
RELEASED BY
MATERIAL:
SEE NOTE 1
FINISH:
±.010
11
151850
1
ITEM
NEXT ASSY
REQD
APPLICATION

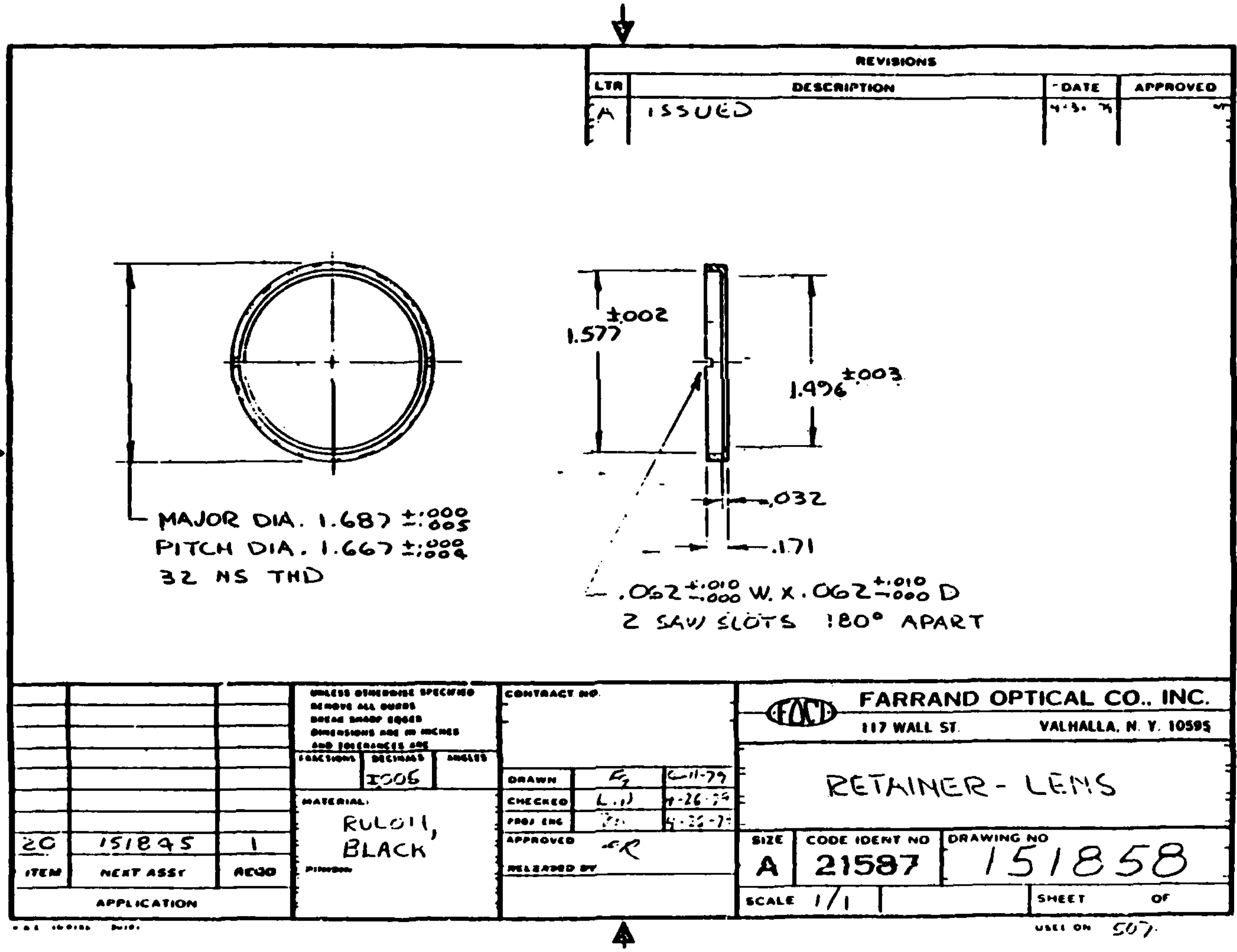


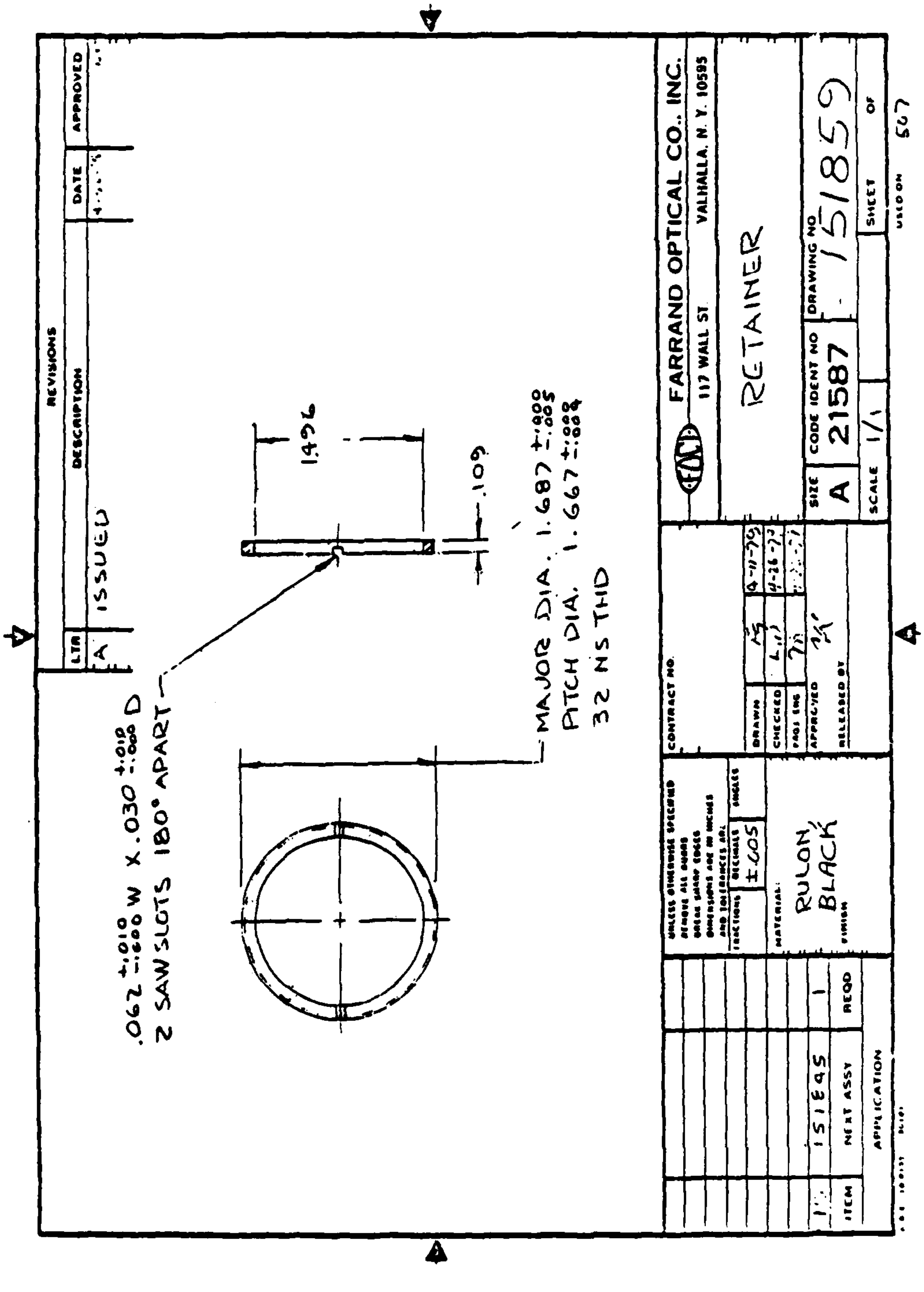
FARRAND OPTICAL CO. INC.
BRACKET - SIDE
H.M.D.
B
21587
151854
SCALE 1:1
REVISIONS
ISSUED
CYCLAC ABS
GR.GSM
DRILL #23 (.154)
4 HOLES
"F" DRILL (.257)
2 HOLES
"C" DRILL (.316)
3.656
2.00
.828
.438
NOTE: CEMENT ANGLES AND BLOCKS USING METHYL-ETHYL-KETONE.

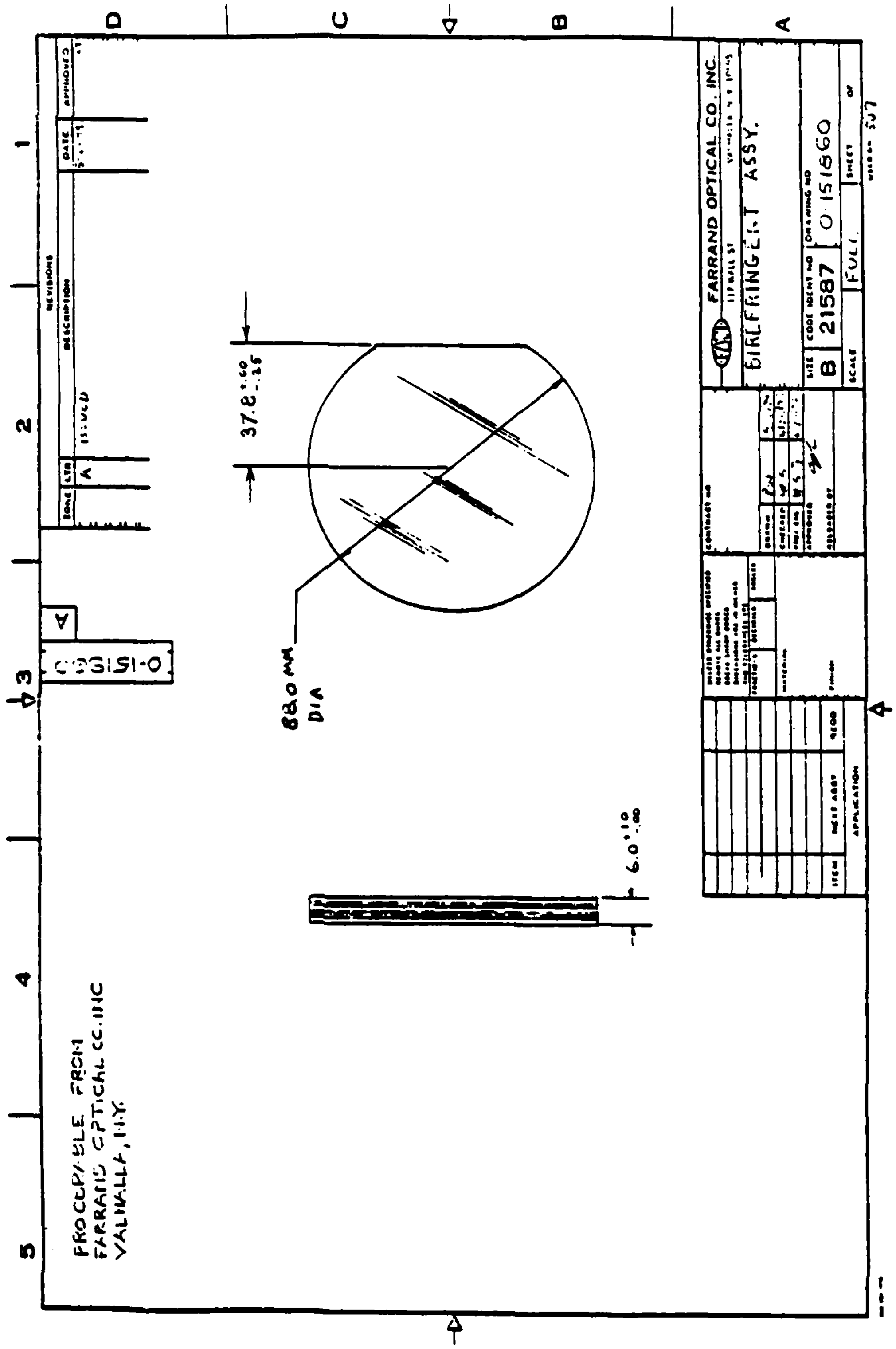

NOTE:
1. WIDTH "W" IS APPROX. FOR REF. ONLY. ACTUAL WIDTH TO BE DETERMINED AT ASSY (151845)
151855-
A
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
2"
(BLANK)
"W"-SEE TABLE
±.001
1.496
-A-
A .001
+.000
-.001
1.575
PART NO.
PART DES.
"W" SEE NOTE 1
-1
A
.122
-2
B
.274
-3
C
.074
-4
D
.120
D
15
151845
-4
C
14
B
13
A
12
-3
-2
-1
ITEM
NEXT ASSY
REQD
APPLICATION
MATERIAL:
RULON, BLACK
FINISH:
CONTRACT NO
DRAWN
CHECKED
APPROVED
RELEASED BY
FARRAND OPTICAL CO., INC.
117 WALL ST
VALHALLA N Y 10595
SPACER-LENS
SIZE
B
CODE IDENT NO
21587
DRAWING NO
151855-
SCALE
SHEET
OF
5
4
3
2
1
D
C
B
A

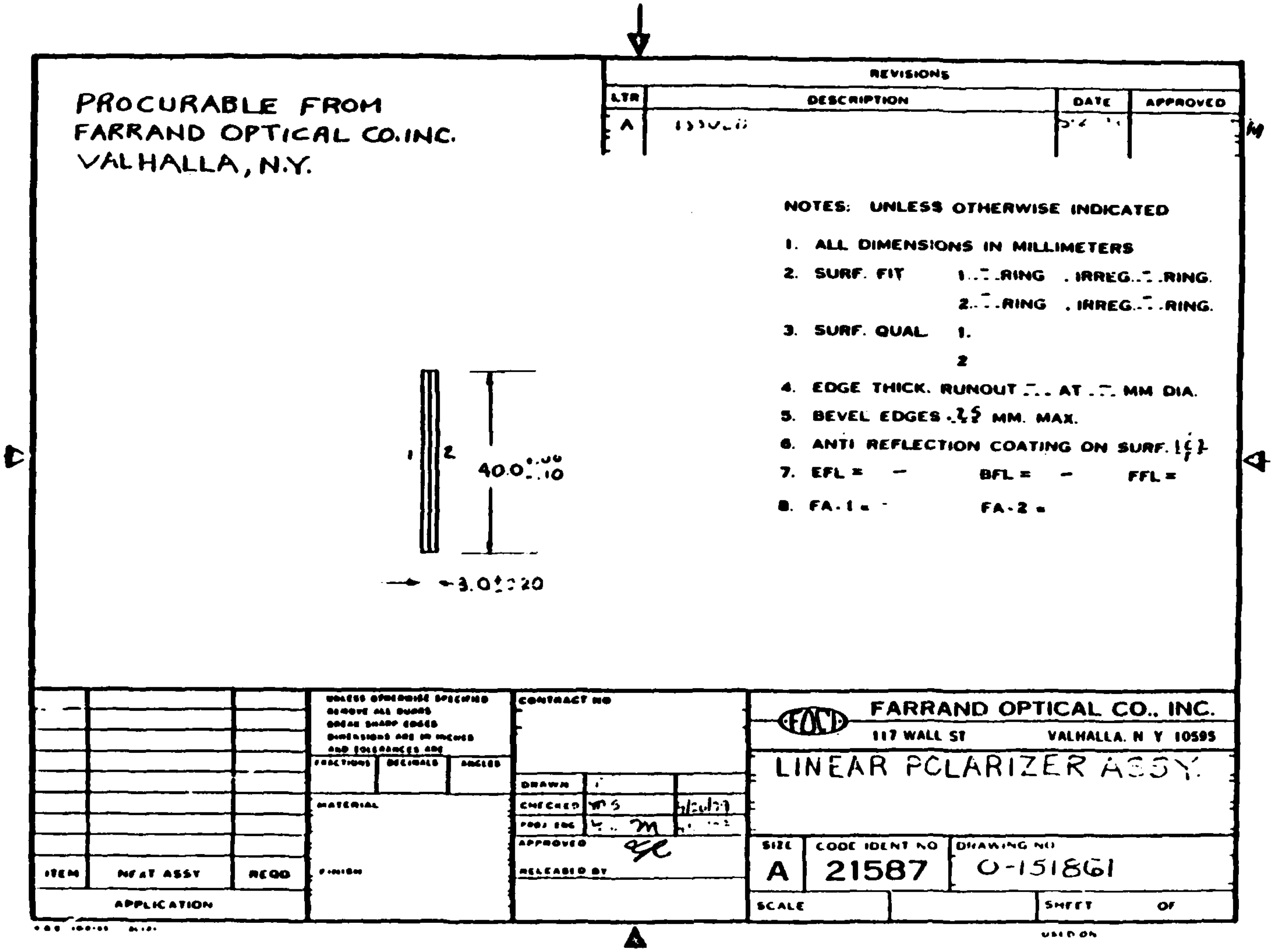

NOTE:
1. DIAMETERS TO BE CONCENTRIC WITHIN .001
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
±.001
.032
±.001
1.338
+.001 −.000
1.419
+.000 −.001
1.575
+.000 −.010
.859
16
151845
1
ITEM
NEXT ASSY
REQD
APPLICATION
MATERIAL:
RULON,
FINISH: BLACK
CONTRACT NO.
DRAWN
FG
CHECKED
PROJ ENG
APPROVED
RELEASED BY
FARRAND OPTICAL CO., INC.
117 WALL ST.
VALHALLA, N. Y. 10595
CELL-LENS
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151856
SCALE 1/1
SHEET
OF
USED ON 507

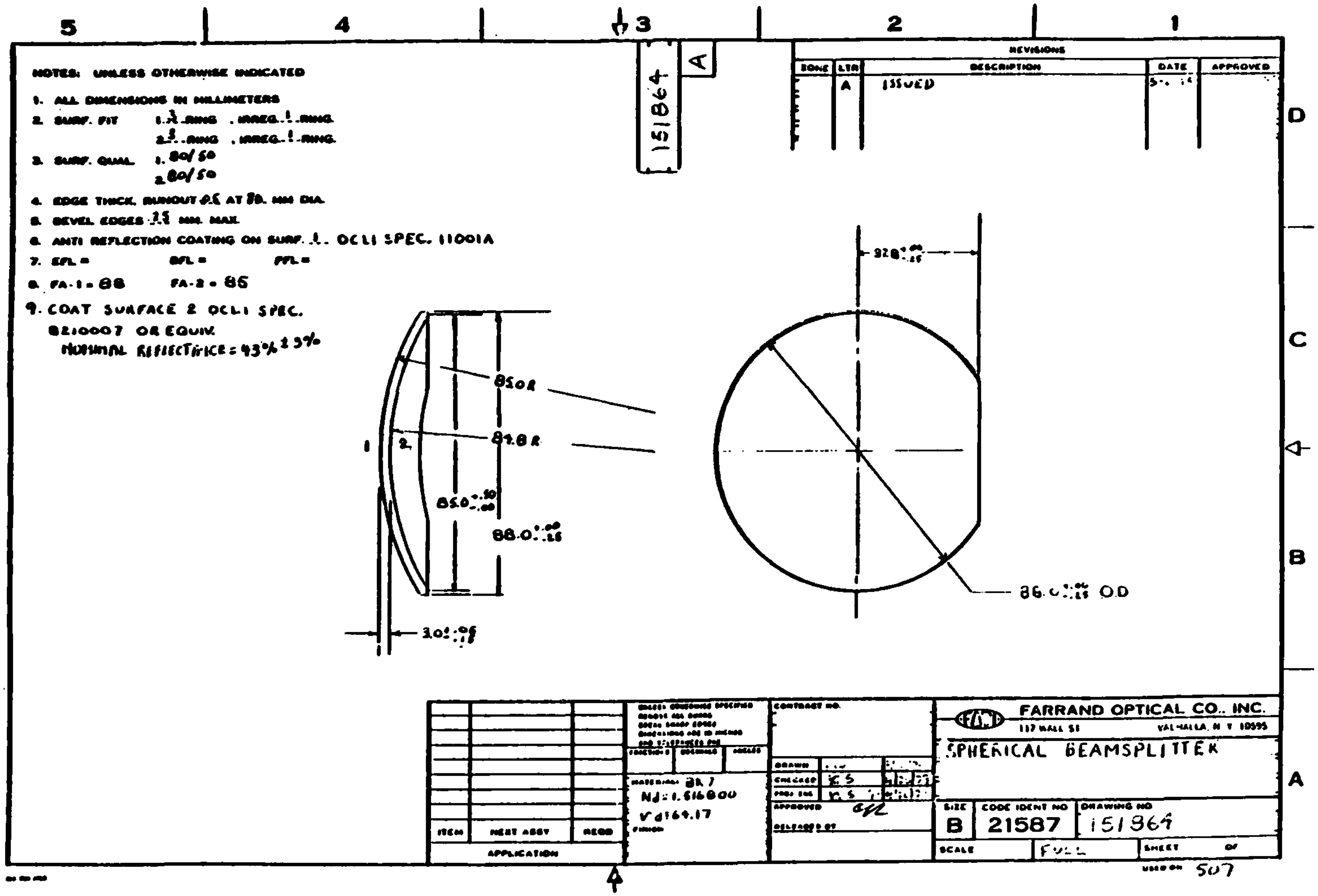

NOTE:
1. WIDTH "W" IS APPROX. FOR REF. ONLY. ACTUAL WIDTH TO BE DETERMINED AT ASSY (151845)
151857-
REVISIONS
ZONE | LTR | DESCRIPTION | DATE | APPROVED
A | ISSUED
2" (BLANK)
"W" SEE TABLE
±.001
1.338
-A-
A .001
+.000 -.001
1.918
PART NO. | PART DES. | "W" SEE NOTE 1
-1 | E | .115
-2 | F | .128
F 17 151845 -2
E 17 151845 -1
ITEM | NEXT ASSY | REQD
APPLICATION
MATERIAL
RULON BLACK
FINISH
CONTRACT NO
DRAWN
CHECKED
APPROVED
RELEASED BY
FARRAND OPTICAL CO., INC.
117 WALL ST VALHALLA N Y 10595
SPACER - LENS
SIZE B
CODE IDENT NO 21587
DRAWING NO 151857-
SCALE —
SHEET OF
507

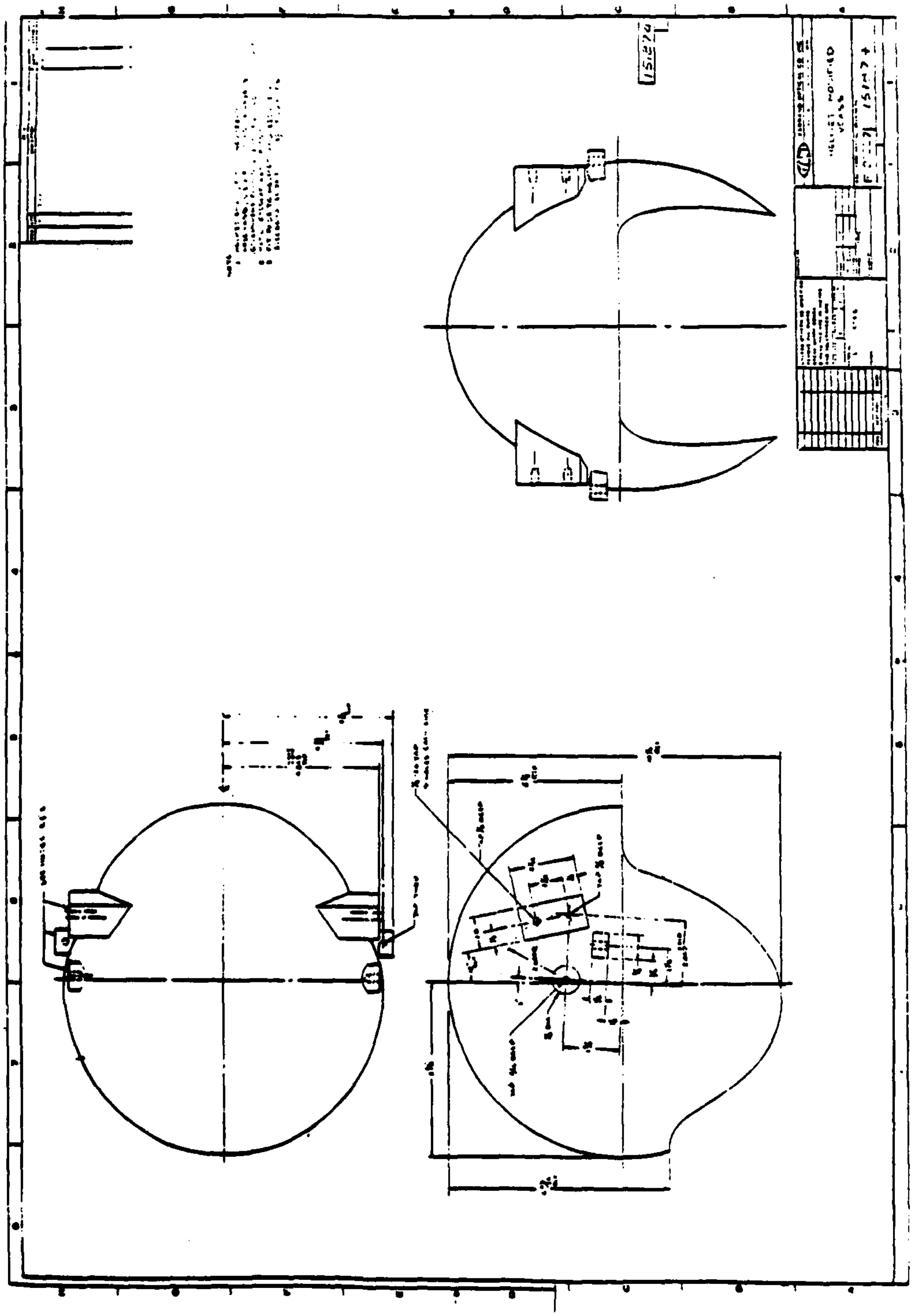

REVISIONS
LTR DESCRIPTION DATE APPROVED
A ISSUED
1.577 ±.002
1.496 ±.003
.032
.171
MAJOR DIA. 1.687 +.000 −.005
PITCH DIA. 1.667 +.000 −.004
32 NS THD
.062 +.010 −.000 W. X .062 +.010 −.000 D
2 SAW SLOTS 180° APART
CONTRACT NO.
DRAWN
CHECKED
PROJ ENG
APPROVED
RELEASED BY
MATERIAL:
RULON, BLACK
FINISH:
DECIMALS ±.005
FRACTIONS
ANGLES
20
151845
1
ITEM
NEXT ASSY
REQD
APPLICATION
FARRAND OPTICAL CO., INC.
117 WALL ST.
VALHALLA, N. Y. 10595
RETAINER - LENS
SIZE A
CODE IDENT NO 21587
DRAWING NO 151858
SCALE 1/1
SHEET OF
USED ON 507


REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
.062 +.010 -.000 W X .030 +.010 -.000 D
2 SAW SLOTS 180° APART
1.496
.109
MAJOR DIA. 1.687 +.000 -.005
PITCH DIA. 1.667 +.000 -.004
32 NS THD
FARRAND OPTICAL CO., INC.
117 WALL ST.
VALHALLA, N. Y. 10595
RETAINER
CONTRACT NO.
DRAWN
CHECKED
APPROVED
RELEASED BY
MATERIAL
RULON
BLACK
FINISH
SIZE
A
CODE IDENT NO
21587
DRAWING NO
151859
SCALE 1/1
SHEET
OF
1
151845
1
ITEM
NEXT ASSY
REQD
APPLICATION
±.005


FARRAND OPTICAL CO. INC.
BIREFRINGENT ASSY.
B
21587
0 151860
FULL
REVISIONS
ISSUED
37.8
88.0 MM DIA
6.0
0-151860
PROCURABLE FROM
FARRAND OPTICAL CO. INC
VALHALLA, N.Y.


PROCURABLE FROM
FARRAND OPTICAL CO. INC.
VALHALLA, N.Y.
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
A
NOTES: UNLESS OTHERWISE INDICATED
1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT 1. RING . IRREG. RING.
2. RING . IRREG. RING.
3. SURF. QUAL 1.
2
4. EDGE THICK. RUNOUT AT MM DIA.
5. BEVEL EDGES .25 MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1&2
7. EFL = – BFL = – FFL =
8. FA-1 = FA-2 =
1
2
40.0
3.0
CONTRACT NO
DRAWN
CHECKED
APPROVED
RELEASED BY
MATERIAL
FINISH
FRACTIONS
DECIMALS
ANGLES
ITEM
NEXT ASSY
REQD
APPLICATION
FARRAND OPTICAL CO., INC.
117 WALL ST
VALHALLA, N Y 10595
LINEAR POLARIZER ASSY.
SIZE
A
CODE IDENT NO
21587
DRAWING NO
0-151861
SCALE
SHEET
OF


NOTES: UNLESS OTHERWISE INDICATED
1. ALL DIMENSIONS IN MILLIMETERS
2. SURF. FIT
3. SURF. QUAL. 1. 80/50 2. 80/50
4. EDGE THICK. RUNOUT
5. BEVEL EDGES MM. MAX.
6. ANTI REFLECTION COATING ON SURF. 1. OCLI SPEC. 11001A
7. EFL = BFL = FFL =
8. FA-1 = 88 FA-2 = 86
9. COAT SURFACE 2 OCLI SPEC. 821000? OR EQUIV. NOMINAL REFLECTANCE = 43% ± 5%
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
A
ISSUED
151864
A
85.0 R
84.8 R
1
2
85.0
88.0
3.0
86.0 OD
FARRAND OPTICAL CO., INC.
117 WALL ST
VALHALLA, N Y 10595
SPHERICAL BEAMSPLITTER
CONTRACT NO.
DRAWN
CHECKED
APPROVED
RELEASED BY
MATERIAL BK 7
Nd = 1.516800
Vd 64.17
FINISH
ITEM
NEXT ASSY
REQD
APPLICATION
SIZE
B
CODE IDENT NO
21587
DRAWING NO
151864
SCALE
FULL
SHEET
OF
USED ON 507



*U.S. GOVERNMENT PRINTING OFFICE 1983/759-106/1311